University of Windsor
Scholarship at UWindsor

Electronic Theses and Dissertations | Theses, Dissertations, and Major Papers

7-17-1966

The effect of rapid heat treating on the mechanical properties of low carbon steel sheet.

James Malcolm Emberly Wallbridge
University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation
Wallbridge, James Malcolm Emberly, "The effect of rapid heat treating on the mechanical properties of low carbon steel sheet." (1966). *Electronic Theses and Dissertations*. 6456.
https://scholar.uwindsor.ca/etd/6456

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email (scholarship@uwindsor.ca) or by telephone at 519-253-3000ext. 3208.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

THE UNIVERSITY OF WINDSOR

THE EFFECT OF RAPID HEAT TREATING
on
THE MECHANICAL PROPERTIES
of
LOW CARBON STEEL SHEET

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF APPLIED SCIENCE

by

James Malcolm Emberly Wallbridge

Department of Engineering Materials

September 1, 1966

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: EC52637

UMI®

UMI Microform EC52637
Copyright 2007 by ProQuest Information and Learning Company.
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABU 3722

ACKNOWLEDGEMENTS

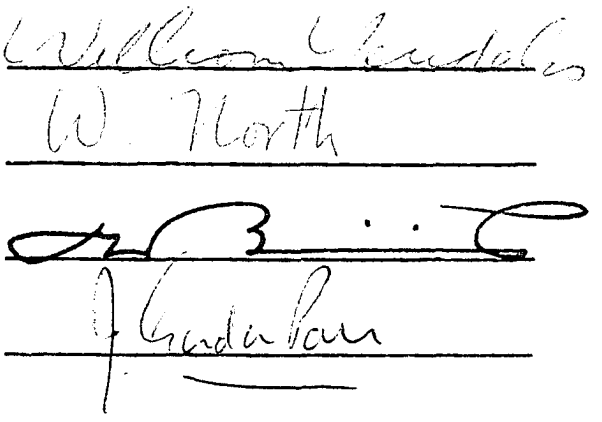
The author wishes to express his gratitude to Dean J. Gordon Parr for his invaluable guidance and unfailing encouragement, to Dr. W. V. Youdelis for many helpful discussions, to my colleagues and friends in the department for their criticisms and advice, and to Professor R. G. Billinghurst for his deparmental supervision. Particular thanks are due Mr. M. L Gindl who showed great patience in the heat treating of the specimens and Mr. J. C. Mercier who did some of the drawings and pictures in this manuscript.

This work was sponsored by Dominion Foundries and Steel, Limited whose financial support was greatly appreciated. Discussions with Mr. W. J. Stewart, Director of Metallurgy, during the investigation were most helpful and are deeply appreciated.

I-7241

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPROVED



Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

A study has been made of the effect of heat treating variables on the mechanical properties of martensitic blackplate. By reducing the soaking time to less than $\frac{1}{2}$ second it has been possible to produce ultimate tensile strengths of 200 KSI with 5% elongation (in 1") in 0.12 carbon steel and 165 KSI with 3.5% elongation (in 1") in 0.07 carbon steel. This gain in strength is associated with a very fine grain size.

The ductility has been found to vary directly with strength after quenching and after tempering. Austenitizing temperature was only important when longer soaking times were used. Tempering, up to $300^{0}C$, of the steel quenched after short soaking times results in a loss of both strength and ductility.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE OF CONTENTS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF TABLES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF FIGURES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

INTRODUCTION

The objective of this investigation was to devise economical methods of producing higher strengths with adequate complementary properties in low carbon steel sheet.

Several possible strengthing mechanisms present themselves: work hardening, solid solution strengthening, small particle strengthening, martensitic hardening, and the production of a very fine grain size. All these mechanisms depend to some extent on producing a structure in which dislocations are pinned by some sort of barrier. The effectiveness of these obstacles depends on two primary characteristics: their strength and their spacing.

Work hardening is at present used as a commercial strengthening mechanism. Higher strengths can be obtained but the ductility rapidly falls off as high strength levels are reached. For some applications this is acceptable: tinplate with less than 1% elongation in two inches can be formed (but marginally) into containers. However, the combination of mechanical properties obtained by cold-working is not outstanding.

The addition of trace amounts of some elements can produce large increases in strength. In particular carbon, nitrogen and phosphorus are to be considered. These are present in all steels, but the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

presence of larger amounts is considered detrimental for various reasons by users, and particularly by the tin can industry.

Fine particles, introduced either through a precipitation process or by intentional addition of some material in a very finely divided state, will pin dislocations. The precipitation process, if a suitable system for precipitation to take place could be found, would be very desirable. Unfortunately, no such economic system, at least in large tonnages, has been found. Several that might be possible are nitrogen with aluminum or vanadium, carbon with niobium. In the case of aluminum, this implies a killed steel which in itself, is more costly due to production problems and higher scrap loss. Vanadium at the present time is in very short supply and therefore unattractive. Niobium is at present under study.[1] All these systems result in a precipitate which is present in a very fine form and is associated with fine ferritic grain size. The fine grain size may in itself be the major strengthening mechanism. The addition of fine particles, as in TD nickel, would also lead to a strengthening; but again, such a process appears to be too expensive to consider for high tonnage items at present.

The production of martensite is a common strengthening mechanism in higher carbon steels. It

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

was once believed that the production of martensite in low carbon steel was impossible due to the inherently low hardenability; but when the thickness of the sheet is taken into consideration, martensitic structures should be attainable by normal water or brine quenching procedures.

It is generally accepted that the strength of martensite is due to a combination of four factors: (1) fine structure (2) internal stress in the units resulting from the transformation (3) interstitial solid solution strengthening (4) precipitation or segregation of the carbon atoms--as carbides. Although we cannot expect low carbon martensite to be as hard as higher carbon material, Bain and Paxton[2] suggest that a DPH of 400 might be obtained from 0.12C material.

A quantitative relationship between strength and grain size of ferrite has been suggested by Hall[3] and Petch.[4]

$$\sigma_y = \sigma_o + kl^{-\frac{1}{2}}$$

σ_y is the lower yield stress
σ_o is the stress due to the friction within a grain on a moving dislocation
k is a constant
l is the grain diameter

The equation is based on the hypothesis that additional grain boundaries constitute the only change in the barriers to dislocation movement with a change in grain size. This relationship has been verified many times. This all refers to ferritic grain size; and since this is difficult or

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

impossible to determine in microstructures involving martensite, bainite or pearlite, it has become customary to relate the strength to the prior austenite grain size. In the past, investigators[5,6] have shown that grain size has little effect on strength over the usual commercial range of grain sizes. This can be explained however by the small change in $l^{-\frac{1}{2}}$ over this range of grain sizes (see figure 1).

Prior austenite grain size is not a good measure of ferrite grain size in an evaluation of martensitic strength because there is not a one-to-one correspondence between austenite grains and martensite units (assumed to be the ferrite grain in this case).

The structure of low carbon martensite may be described as long thin units collected into bundles. The units are parallel in each bundle and the bundles are in small groups defined by the prior austenite grain boundaries. Thus grain size in martensite is very much more complex than in polygonal structures. Because of the acicularity of the units and their combination into bundles we cannot even be sure what is a "ferrite" grain. The martensitic microstructure therefore may not be capable of description in terms of the prior austenite grain size or any other grain size for that matter. It might be thought that the length of the plates or needles would be a reasonable indication of size, but most of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the possible slip planes in a martensite unit are limited by the width rather than by the length of the unit; therefore the width is probably a better criterion.

It is so much easier to measure prior austenite grain size that this will continue to be used by most other investigators and by us. Some justification for this practice is found in Zackay's work[7], which indicates that there is a nearly one-to one correlation between prior austenite grain size and martensite unit length (figure 2).

Phillips[8] has suggested that austenite grain refinement only affects the larger units and in these units the width is reduced at only half the rate the length is. The finer half of the structure is relatively unaffected by changing the austenite grain size. Since the wider units will be weaker, considering their area, the width of these units should be used in a Petch type equation.

Fussell[9] has found that for a five fold decrease in austenite grain size from 34 to 7 μ a four fold decrease was obtained in length and a threefold decrease in the width. The effect of refinement in martensite was one of cutting off the higher end of the spectrum of sizes rather than of changing the mean of Gaussian distribution--which is the effect in a polygonal structure

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Since the prior austenite boundaries are all included in a consideration of bundle boundaries, grain size effects in martensite may be described entirely in terms of bundles and units. Crussard[10] has therefore re-written Petch's flow stress equation for martensite as

$$\sigma_y = \sigma_o + k_1 l^{-\frac{1}{2}} + \alpha k_2 l^{-\frac{1}{2}}$$

where the symbols have the same meaning as in Petch's equation. The constant k_1 is the influence of grain size, on the density of dislocation tangles resulting from deformation (the finer the grain size the higher the density of tangles for a given strain). The constant k_2 is related to the number of dislocation stored at the boundaries in the process of transmitting slip through them, while α is related to the shape of the boundaries. These constants, though, cannot be accurately determined and therefore an accurate assessment of the change in flow stress due to changes in microstructure cannot be accurately made with this equation.

Kelly and Nutting[11] as well as earlier investigators have found that in low carbon steels the martensite consisted of single crystal needles. The absence of twinning in these needles is reflected

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in the Widmanstättan form of the carbide produced on tempering and the appearance of dislocations in the needles. This constrasts with higher carbon material in which martensite consists of internally twinned plates. Two possible reasons were propounded for the change in morphology with carbon content. "First, the stacking fault energy of austenite may increase with carbon content. This is consistent with the increase in relative numbers of internally twinned plates with carbon content. On the other hand, the change in morphology may be temperature dependent. The autotempered precipitate is never seen in the twinned martensitic plates, suggesting that these plates are formed in the low temperature portion of the transformation range. Since the proposed transformation mechanism for martensitic needles involves a relatively large first shear (19.5°) it is possible that this type of transformation would be assisted by the thermal motion of the atoms. Thus as the transformation temperature range moves to lower temperature with an increase in carbon content, the percentage of martensite needles will decrease until M_s is below a temperature at which the thermal motion is sufficient to aid the reaction. Below this temperature the martensite will be entirely in the form of plates."

West[12] believes that a profusion of lattice defects is present in rapidly reaustentitized structures.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

These would increase the strength of the martensite if they are quenched in.

Dubé[13] has recently made a strong argument favoring the theory that the presence of high dislocation densities contributes a large part of the strength of martensite by interacting with the stress fields around the carbon atoms--at least in very low carbon martensites. Short soaking times might be expected to increase the density of dislocations and thereby might increase the strength in this way.

Cohen[22] has shown that the flow stress varied as the square root of carbon concentration in material in which aging had been prevented or was corrected for in subsequent computations. He has also shown that aging can take place even at -40°C in low carbon steels. Short soaking times here might have an adverse effect in that, depending on prior treatment, all the carbon may not get into solution with short soaking times. If such an effect were very significant it might be moderated by a prior conventional quench--although this may increase the austenite grain size compared to that produced from a heavily cold worked structure.

McFarland[14] has obtained the following results by quenching steel similar in composition to that used in this work.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CARBON CONTENT %	ULTIMATE STRENGTH KSI	YIELD STRENGTH KSI	ELONGATION % in 2"
.10-.12	180	140	3.5
.06-.09	165	125	3.6

The austenitizing time is not stated, but since the process involves a continuous heat treating unit, presumably it was short.

Grange[15] working with a higher carbon alloy steel (AISI 8640) has developed two methods of producing very small grain size. One involves working the material just above A_3. The other method involves repetitive short austenitizing treatments. By these methods he has developed grain sizes to ASTM 16, and as a result obtained a gain of 50,000psi in yield strength over the value of 225,000psi obtained by conventional heat treating.

Phillips[8] has obtained an increase of 10% in yield strength and 5% in ultimate tensile strength by using a four second soaking time on 0.27C material.

A gain of 50% in ultimate tensile strength by multiple rapid austenitizing treatments, was indicated in preliminary work at the University of Alberta.[16] This work was done on 0.4C alloy steel.

Changes in microstructure that are too small to observe under the light microscope might

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

be elucidated by measurement of x-ray line widths. The width of diffraction lines can be ascribed to three primary causes. (1) Inherent width, due to the experimental set up (wavelength spread of the radiation used, finite width of the sample, misalignment of the apparatus, mosaic structure). (2) Thickness of the individual crystallites--the thinner the crystals the wider the peaks will be. (3) The presence of non-uniform strain within the crystal. The last two causes are difficult to separate and therefore the presence of line broadening only indicates that one or the other is present unless a very careful analysis of the data is made. The first cause presents no problem in that it can be corrected for by using a standard specimen.

BLACKPLATE[17]

This name is applied to steel sheet which is normally used for the production of tin plate. The name comes from the appearance of the sheet in earlier days when it was entirely processed by hot rolling, and as a result an oxide layer was present on the surface giving it a black colour.

Steel for the production of blackplate is produced by either the basic oxygen process or the open hearth. Most of the steel used is rimmed because of the better surface for rolling and the lower cost. Normally,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

for the production of blackplate the hot rolled strip is given a cold reduction of 80-90%. This can be conviently be done on a five stand four high tandem mill or in smaller operations on reversing mills. Cold rolling produces a hardened material whose yield point and ultimate tensile strength are appreciable higher than those of the original material, with corresponding loss of ductility.

After cold rolling, it is necessary to restore some ductility to the blackplate so that it may be plastically deformed during subsequent shaping operations such as can making. Hence some form of annealing is essential at this stage. The resulting mechanical properties obtained in a given strip will depend on type and conditions of the annealing process.

Box or Batch Annealing

In this process the blackplate is usually heat treated in coil form in a protective atmosphere to prevent scaling. It has been found desirable to anneal the coil (in batch furnaces) at 1150 to 1250^{o}F for a period of 4 to 12 hours. A clear bright relatively oxide free coil product can be obtained if a deoxidizing gas is circulated around the coil while the temperature is over 250^{o}F.

Continuous Annealing

In this process the finished cold worked product is uncoiled and passed through a furnace in which

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

it is heated to 1200°F in a protective atmosphere. The blackplate moves through the furnace at speeds up to 6000fpm. The continuously annealed strip is inherently stiffer than the box annealed strip because of the lack of time for grain growth to occur; but it still possesses adequate ductility to provide good formability.

Batch annealing, with its longer soaking times and slower cooling, produces a steel that is very ductile. Low capital and operating costs are also characteristic of this process. The significant temperature gradients which occur in the coils of blackplate during the heat treatment result in non-uniform mechanical properties. Because the times required for box annealing are lengthy, large tonnages of material are tied up in the box annealing plant. Also, due to the large amounts of metal heated (a coil of blackplate weighs 7-20 tons) the thermal cycle is rather inflexible.

In the continuous process more uniform mechanical properties are realized, and appreciably less stock is tied up than in the batch anneal. The conditions of heat treatment are much more flexible since only a small amount of the metal is heated at one time.

Due to the short duration of the heat treatment given, grain growth does not occur. Hence the very ductile grades cannot be produced. On the other hand, higher strength grades can be easily produced, and there-

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

by a thinner blackplate can be used to achieve equivalent strength. It has been pointed out by Murray[18] that by varying the final annealing process, there is a possibility of producing from the same cold-rolled low carbon steel sheet, finished products with a wide variety of mechanical properties.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

EXPERIMENTAL PROCEDURE

The best means of developing higher strength appeared to be through the production of a fine grained martensite. Since previous results[15,16] had indicated that short soaking times would produce this fine grained martensite in higher carbon steels, it was decided to investigate, in low carbon steel sheet, the effect of the following variables: soaking time, soaking temperature, prior structure, carbon content, tempering time and tempering temperature. "Short" soaking times will here be those of less than one second duration while "long" soaking times will be those over twenty seconds. Rapid heat treating will refer to a process involving fast initial heating, short soaking time, and then a fast quench.

The apparatus shown in figure 5 was built for the investigation. Self-resistance heating was used--due to the ease of control and the fast heating rates obtainable. The power is varied to control the heating rate and the soaking temperature. A typical heat treating cycle involves heating at about 1000°C/sec. to the desired soaking temperature, holding isothermally for the desired time and then quenching at over 2000°C/sec. The problem of obtaining reproducible heat treating cycles led to the investigation of two experimental techniques: manual and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

timed control, and complete electronic control.

Manual Control

Early experiments employed a timer (manually set) to control the length of the initial heating and thereby the temperature reached, and then manual control of the soaking temperature with resistor 2 (figure 4). This was not completely satisfactory in that small fluctuations in the resistance of the circuit resulted in large variations in the temperature reached on heating. Manual control of the temperature after attainment of holding temperature was more satisfactory but still not ideal, since it was subject to human error.

All specimens from sheets 13267 and 18439 were heat treated manually. As is discussed later, this led to fairly large errors; therefore a change was made to the following system.

Electronic Control

Switches were placed on the balance wheel of a recorder used to measure temperature sensed by a thermotrio (described in the next section). The circuitry was arranged to provide three separately controlled power sources, which will be called "primary","holding" and "booster". One switch controlled the primary heating circuit, which supplies the energy

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

for the initial heating. This switch had to be set to turn off the primary power about one hundred degrees under the desired temperature due to the lag in the system (time to close relays, arcing across contacts, etc.). The other two switches act as lower and upper limits for soaking temperature.

Operation of the apparatus is as follows. Upon closing the starting switch (figure 4) the timer starts running and both the primary and the holding power switch on. When the temperature corresponding to the setting of the first switch is reached, the primary power switches off. The temperature continues to rise (because the holding power is still supplied) and upon reaching the preset lower temperature limit the booster power turns on (this power keeps the temperature above the lower limit) and stays on until the third switch is tripped. If the temperature again falls to the level preset by the second switch the booster power cuts in again. The three powers are appoximately in the ratios 1000-100-2. Normally, the second and third switches are set ten degrees centigrade below and above the desired soaking temperature respectively. After the desired time (as set on the timer) has elapsed, all power is turned off and a solenoid is activated which allows the sample to fall into flowing water. The water is contained

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in a bath with thirty sprays on each side of the sample, placed perpendicular to and one half inch from the sample.

Tempering

Samples which were to be tempered were suspended in an organic bath to which a total reflux condenser was attached. This enabled the desired temperature to be maintained within $\pm 0.5^{\circ}C$. The baths used were as follows.

Desired Temperature	Actual Temperature	Fluid
$100^{\circ}C$	$98.5^{\circ}C$	Propanol
$200^{\circ}C$	$198^{\circ}C$	Ethylene Glycol
$300^{\circ}C$	$290^{\circ}C$	Glycerin

Thermotrio

The conventional thermocouple cannot be used to measure the temperature of the specimen because of the voltage drop across the junction--due to the heating current flowing through the sample. Duwez[19] suggested the use of three wires to overcome this problem. The three wires (in our case alumel-chromel-alumel) are welded on the sample in a close row (figure 10), the two outside wires being identical. Any combination usable as a thermocouple could be employed. A variable potentiometer, placed across the outside

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

wires, is adjusted until no jump can be observed in the output of the thermotrio when a potential is applied across the sample.

Tensile Specimen Preparation

Tensile specimens were prepared to ASTM E8 (half size) with a one inch gage length, a width of 0.250 ± 0.010, and a thickness of 0.050 to 0.080". They were initially shaped by punching them from the heat treated strip with a die (figure 6). Due to the high strength of the material it was necessary to use negative clearance, and even so the edges were not satisfactory. Due to warpage of the specimens from heat treatment, further distortion occurred during the punching, resulting in unclean shearing action. The edges of these samples were honed in an attempt to produce reliable specimens, but even so the early data reveal a scatter in tensile results due to stresses set up during punching.

Consequently, the preparation procedure was changed to one of grinding on a TensilGrind machine. This machine uses a contoured grinding wheel turning at about 3400rpm. The specimens, inserted in a special holder (figure 9) are guided against the grinding wheel by a contoured master template attached to the holder. To further improve the ground edges,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

as well as to remove scale, the specimens were chemically polished. Initially solution 1 and then 2 (table 2) were used but later solution 3 was employed: it is faster and produces a better surface. (It should be noted that this solution is very active when hot, and care has to be exercised against the foaming which results from continued use--due to the almost explosive decomposition of the hydrogen peroxide.) Widths of the tensile specimens were measured with a micrometer while the thickness was measured with a dial gage ($\pm$0.0001"). The specimens as polished usually varied in thickness by about $\pm$ 0.0003" but sometimes by as much as $\pm$0.001". In all cases the thickness was taken as that at the section of minimum area.

Micrography

In an attempt to determine grain size several etchants were investigated. Nital (3% HNO_3 in ethanol) revealed some structure, but the prior austenite grain boundaries were not revealed. An etchant of 5 ml. nitric acid in 100 ml. butanol with 1 gram of benzalkonium chloride (a wetting agent) added gave very good contrast in the martensitic structure; but, again, the prior austenite grain boundaries were not revealed. The most satisfactory etchant for revealing prior austenite grain boundaries

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

was found to be 5 ml. hydrochloric acid and 1 gm. of picric acid in 100 ml. of ethanol. All photomicrographs in this thesis were etched with this solution. Quoted grain sizes were determined by comparison with standard ASTM charts, used at higher magnifications. Since the grain boundaries are not completely clear, in many cases too small an ASTM number--that is, too large a grain size--has probably been derived.

Impact Samples

Samples for impact tests were machined and ground from stacked heat treated strips (950°C soaking for $\frac{1}{2}$ sec.) to conform to Charpy type A specimens. These were then placed in a holder shown in figure 9. This holder separates and bends easily in the plane of the strips but not in any other. To determine the effect of the holder on observed energy values, standard specimens of cast iron were tested both in and out of the holder. The difference in values (0.9 ft. lb.) is assumed to be due to friction in the holder and has therefore been subtracted from all other results.

X-ray Specimens

Specimens for x-ray diffraction studies were cut from the pieces of sample that remained after cutting the tensile specimens.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Sample Testing

Tensile specimens were tested in an Instron Universal testing machine using wedge action jaws. Due to the warpage in the samples some specimens did not pull uniaxially; but the number of these was small. Loads were measured with standard D and GR Instron load cells, which were calibrated before use and rechecked afterwards. The largest deviation from the beginning to end of a test (drift in calibration) was less than 0.5% which could barely be read. Extensions were measured by the standard strain gage extensometer which was calibrated against a high precision micrometer (2/100,000"). Drift in this system reached ±0.2% in 1" but this was not considered to be significant.

Initial results were read from a load vs time graph, because at this time the extensometer was not operational. A figure approximating the yield strength can be read from these graphs since elongation is approximately proportional to time. When the extensometer became opperational both loads and extensions were recorded by the x-y recorder and values taken from this record. Yield loads in this case were taken as the load at 0.2% offset from the straight line portion of the curve.

Elongations were taken as the difference

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

between the initial reading (the extension of the straight line portion of the curve to zero load) and the point of the curve where an abrupt fall in load took place. Load-extension curves for this material continue rising or stay level until fracture is observed to begin coincident with the abrupt fall in load. The above method of measurement of elongation is not according to ASTM specifications. The values obtained will differ from those obtained by the standard method (measurement of gage marks with the specimen fitted together after failure) due to two primary causes. The elastic strain is included in the strain measured by our method and the strain taking place after initiation of fracture is not included. The standard method introduces uncertainty due to fitting errors. This is significant when very thin samples such as ours must be fitted together. The two errors will tend to cancel each other and therefore our results should have a similar accuracy, to the standard method, and were found to be much more precise. Elongation could be satisfactorily read to ±0.2% elongation in 1".

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

RESULTS*

The results obtained from the tensile tests are given in tables 3to 17. These are then represented in figures 11 to 37 and 58 to 63.

The data from the impact tests and the x-ray analysis are given in figure 46 and tables 18 and 19 respectively. Figures 51 to 57 are photomicrographs of typical specimens.

Figure 11 shows only ultimate strength and figures 12 and 13 show only ultimate strength and yield strength beause the extensometer, at the time these results were obtained, was not operational. Figures 14 to 43 and 58 to 63 were obtained using the extensometer with results being taken off the load-extension graphs.

Figures 17 and on were produced using ground tensile specimens; and, as can be seen, the scatter has been substantially reduced. The remaining scatter is primarily due to errors in measurement of the thickness of samples, measurement of soaking time, and through variation of the temperature during heat treating.
It can be seen that the following properties can be obtained

Treatment	UTS KSI	YS KSI	Elongation % in 1"
$\frac{1}{2}$ sec. 925°C 0.12C	200	160	5

*Straight lines shown on the graphs do not necessarily indicate that a functional relationship exists.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

½ sec. 950°C 1 min. 300°C 0.12C	170	150	3.5
½ sec. 950°C 100 min. 300°C 0.12C	150	140	2.5
½ sec. 950°C 0.07C	160	130	3.5
½ sec. 950°C 100 min. 300°C 0.07C	140	130	2.5

A ductile/brittle transition temperature can be assessed either from the values of energy absorbed or from fracture surface appearance. The energy transition, as shown in figure 46, occurs in the temperature range -20°C to -70°C. The sample tested at 150°C has a rough surface (figure 49) and the individual sheets have necked. The other samples (figure 50) show almost no necking and a typical cleavage fracture at about 45° is observed; therefore, the transition temperature determined by fracture appearance lies between 27°C and 150°C. The heat treated material had the same room temperature value as the material in the as-received condition (ready for delivery to customers).

The x-ray diffraction line breadths (table 19) are narrowest with material given the shortest low temperature soaking treatment. This

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

material has the smallest grain size and the highest tensile properties.

Figures 58 to 63 show that the cold worked material has lower strengths after quenching than annealed material.

UNIVERSITY OF WINDSOR LIBRARY

14724

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

DISCUSSION

As can be seen on all graphs relating to soaking time, the tensile properties have been improved by a reduction in holding time. This is to be expected in that on heating, nucleation of austenite is fast,[20] while growth is slow; therefore, with a short soaking time the austenite grains are smaller. On quenching, the grain boundaries form an impenetrable barrier resulting in smaller martensite units. According to the modified Petch theory, this would result in a higher yield strength.

The increase in ductility associated with this higher strength was completely unexpected. Both may be a result of a decrease in a tendency to cleavage failure with a reduction in soaking time (due to a finer grain size). This is supported by the following equation[21] which defines a limiting condition for the formation of a large crack from slip bands. When the left side exceeds the right a crack can grow catastrophically to failure.

$$\sigma_y K_y d^{\frac{1}{2}} = \beta \mu \gamma$$

$\beta \simeq 1$

γ surface energy

σy yield strength

$2d$ grain diameter

μ shear modulus

K_y variation of yield stress with grain diameter

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

A reduced grain size will reduce the left-hand side of the equation and therefore reduces the chance of brittle failure.

If a great deal of scale had formed on the specimen and it had therefore to be very heavily chemically polished--and hence reduced in thickness--anomalous results were observed.

Yield strengths plotted against grain size, in figure 45, show surprisingly little scatter in view of the difficulties in determining grain size. Photomicrographs, figures 51, 52 and 57 are typical of specimens given short and long soaking treatments. The difficulty in determining prior austenite grain size is obvious, but a definite difference can be seen. The optical microscope will not resolve the width of the martensite units. Besides this, the midribs of the units--not the edges-- are observed; and since there may be unresolved units between the ones observed it would be unwise to suggest that the distance between the observed ribs is the width of a unit.

Comparing figures 17 to 25 it is seen that both soaking time and temperature influence the tensile properties. At 875°C the maximum strength has not been reached. This is probably due to incomplete solution of the carbon. At short

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

times the strengthsat 925°C and 975°C are similar but with increasing time the strength declines faster with the 975°C soaking temperature. An unusually high elongation is observed when a short soaking treatment at 925°C is used; this may be related to the very narrow x-ray line widths observed with this material. It might be that under these conditions less defects are formed in the steel or that a slightly different substructure is formed. This change in elongation was the only mechanical property change that could be associated with the great change in x-ray line widths with soaking temperature. It would be expected that the line widths would be narrower for the coarser grained material (longer soaking time) but the converse is observed; this is very difficult to explain.

The variation of strength with carbon content (figure 47) is similar to that shown by McFarland (figure 48). The difference is presumably due to the smaller grain size of our material. The ductility, as measured by elongation, increases with an increase in carbon content--or, perhaps it would be more accurate to suggest that it increases with strength. The properties of the quenched material can thus be varied a great deal

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

by a change in carbon content, even at these comparatively low carbon levels. Since the maximum strength that can be produced by double reduction (cold rolling) is about 100 KSI and because the quenched material with 0.05% or more carbon has a minimum strength of 150 KSI, intermediate values (between 100 and 150 KSI) if desired could be obtained by tempering. This would avoid the expensive production of steels containing less than 0.05% C.

Figure 44 shows the relationship between strength and ductility more explicitly: points on this graph represent all samples of 0.12% C quenched from 875°C or above--tempered or not. Normally, elongation is expected to fall as strength increases, but here the converse is observed, The low ductility of samples given long soaking times might be attributed to decarburization, but decarburization could not be found either by microexamination or by microhardness traverses across the sample. Further, ductility would normally be expected to increase with an increase in decarburization: hence in samples given long soaking times we would expect to observe an increase in ductility, rather than the opposite. The tempered samples show the same concurrent increase of strength and ductility and here the soaking time is constant. This could be observed both

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

when comparison was made within one group of samples given the same treatment, and when groups given different tempering treatments were compared. It appears therefore that the relationship is primarily between elongation and strength, the higher elongation avoiding premature, brittle failure. The intermediary, which causes the change in both strength and elongation is presumably the grain size, but some other structural feature may be associated with the tempering results.

No age hardening could be observed in samples held either at room temperature or at 100°C. Since a minimum of two hours elapsed between the time a specimen was quenched and pulled, aging, which has been reported by others,[13] could have taken place during this time, reaching a constant value prior to any test.

During tempering, strength was found to decay exponentially with time, but again, elongation decreases with decreasing strength as was mentioned earlier. Normally, elongation increases with tempering although McFarland[14] also reported a decrease in elongation due to tempering (up to 300°C). The result of tempering on the microstructure is shown in figures 53 to 56. These microstructures could not be differentiated from those obtained by standard treatments other than by the fine grain size.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The results show that increased strength in the as-quenched condition is associated with better ductility; and a lowering of strength, during tempering, is associated with lower ductility. While neither of these sets of circumstances is common in the relationships of properties of higher-carbon steels, some rationalisation is possible.

First, the shape of the sample involved in the tensile tests in this work is one in which a lack of ductility may cause premature failure, and hence potential strength is not attained. It is difficult to sustain this contention with quantitative data, because most work that relates ductility and strength has been performed on circular section samples; but the qualitative truth of the contention to some extent is demonstrated by the lower figures for elongation that pertain to strip samples.

Hence it is not unreasonable to suggest that any structural features in samples of this sort, which enhance ductility will probably be reflected, also, in an improved strength. The structural feature that offers improved ductility in samples that are soaked for short times is, most probably, the small grain size.

During tempering, the grain size is, of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

course, not affected. But, among the complexities of the tempering process, a loss of ductility at low tempering temperatures is not uncommon. The reasons for this effect have been the subject of many investigations, but no completely satisfactory conclusions have been made. Since it is not the purpose of this thesis to investigate the matter, we must be content to observe that the reduction of ductility at low tempering temperatures is demonstrated in the low carbon steels investigated.

The lowering of ductility affects the ultimate tensile strength much more than it affects the yield strength. This is consistent with predictions that might be made from Crussard's equation,[10] set down on page 6: quenched-in stresses are relieved, precipitation of carbides is initiated. Hence a lowering of the yield stress is to be anticipated but it will not be large.

The decrease in elongation as a result of tempering may be associated with blue brittleness. It is interesting that the 0.12C material tempered at 300°C had greater elongation than that tempered at 200°C, while the reverse was true of the 0.07C material. It is believed that only the 0.12C material is blue brittle, with the maximum brittleness being observed when temperatures near

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

200°C are used in tempering. The loss in ductility with temperature in the other cases is ascribed to the relationship which we found to exist between strength and ductility. This is supported by the way the points on figure 44, from tempering results, fall on the same line as the points obtained from the as-quenched material.

It can be seen that the response to heat treatment of the 0.07C material is similar to that of the 0.12C material (figures 29 to 37). The structure in figure 56 indicates that the gain in strength with short soaking times in the 0.07C material may be associated with a small grain size as well. This sample has been tempered--but this will not, of course, change the prior austenite grain size. The grain boundaries are however more easily visible.

The A_3 temperature of this material is about 900°C--which causes the step in figures 29 to 34. On the low side of this temperature the material is simply annealed and therefore its strength is low and ductility high. Above 900°C austenite is obtained on heating, and therefore, martensite is produced on quenching: this results in the stronger structure. Within the range 850-900°C results are unpredictable, because of inevitable variations in composition which results in a mixed structure.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Since the time during which annealing can take place is less in figures 29 to 31 the values are more characteristic of a cold rolled material than those in figures 32 to 34. The tensile properties vary in the same manner with time at temperature (figures 35 to 37), when a martensitic structure is produced, and for the same reasons, as the 0.12C material.

There is no standard method of determining impact values for this thin sheet material. Notched tensile specimens indicate notch sensitivity, but the effects of high strain rate are not accommodated. We therefore devised the experimental method described in an earlier section, to assess a ductile/brittle transition temperature. The results obtained by this method have been very encouraging, although each specimen requires nearly a week to complete. It must be remembered, that these results are only comparable within themselves, and the numerical values should not be compared to such standard critera as the 15 foot-pound ductile/brittle transition. The stress system at the notch is quite different from that in the standard Charpy or Izod sample, due to the discontinuities between laminates.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The initial condition of the material given short soaking has a large effect on the resultant properties. The use of a preliminary soak at 950°C for 30 seconds before rapid heat treating leads to less scatter in the strength of the material but the ductility is much less (figures 26 to 28). If a cold worked material is used, much lower strengths are realized (figures 58 to 63). This might be corrected by a preliminary soak at annealing temperatures before the final rapid heating to austenitizing temperatures. There is a possibility that the cold worked material may not have been fully quenched due to its greater initial thickness (0.0097 compared to 0.0077).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

SUMMARY AND CONCLUSIONS

(1) Elongation varies directly as ultimate strength increasing to 5% in 1" at 200 KSI in the 0.12C steel.

(2) Grain size varies directly as soaking time, ASTM #13 being produced with times less than 0.5 second.

(3) Strength varies inversely as soaking time increasing to 200 KSI for 0.12C and 165 KSI for 0.07C with times less than $\frac{1}{2}$ second.

(4) The notch ductility of the heat treated steel is difficult to assess and the results suggest the necessity for further work.

(5) Tempering results in reduced tensile properties.

(6) The 0.12C steel tempered at 200°C is embrittled.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

SUMMARY AND CONCLUSIONS (CONT'D)

(7) Short soaking times give the narrowest x-ray lines, particularly when low soaking temperatures are employed.

(8) The use of cold worked steel does not lead to as desirable tensile properties as can be obtained from annealed material.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

BIBLIOGRAPHY

1. J.J. Irain et al - JISI, 204, 1966, 702

2. E.C. Bain & H.W. Paxton - "Alloying Elements in Steel", 1961, ASM, Cleveland

3. E.O. Hall - The Deformation and Aging of Mild Steel; III Discussion of Results, Proc. Royal Soc, B64, 1951, 747

4. N.J. Petch - JISI, 174, 1953, 25

5. E.J. Tanitsky & M. Baeyertz - The Marked Similarity in Tensile Properties of Several Heat Treated SAE Steels - As refereed to in Reference 15

6. Metals Handbook, 7th ed. ASM, Cleveland, 1939, 515

7. V.E. Zackay - Strengthening Mechanisms of Solids 1961, ASM, Cleveland

8. R. Philips - BISRA - Private communication

9. Fussel - Private communication

10. C. Crussard - Austrailian Institute of Metals Journal 8(3), 1963, 317

11. P.B. Kelly & J. Nutting - JISI, 199, 1961, 199

12. A.S.SSastri & D.R.F. West - JISI, 203, 1965, 138

13. A. Dube - AIME Fall Meeting 1965

14. W.H. McFarland - Trans. Met. Soc. of AIME, 233, 1965, 2028

15. R.A. Grange - Trans. ASM, 59 1966, 26

16. J.M. Wallbridge - 4th Year Project; Dept. of Mining & Metallurgy, University of Alberta, 1964

17. The Making Shaping & Treating of Steel, US Steel 7th ed. 1957

18. G. Murray - The Effect of Different Heat Treatments on the Mechanical Properties of Steel Strip, BISRA Ref. MH/H/26/59

19. O.A. Boedtker & P. Duwez - Report #3 to O.N.R. CIT (Pasadena) March 1962

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

BIBLIOGRAPHY (Cont'd)

20. L. Howarth - Trans. ASM, 58, 1965, 476

21. A.H. Cottrel - Trans Met. Soc. of AIME, 212, 1958, 192

22. M. Cohen - JISI, 201, 1958, 192

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX

Because this project involves economic considerations it is appropriate to make a brief analysis of the costs of the project itself.

CAPITAL COSTS

HEAT TREATING APPARATUS

RECORDER	$2400
HOIST	280
HEAT TREATER	335
BATTERIES CHARGER ETC.	575
WATER PUMP	225
TENSILGRIND MACHINE	1250
	$5065

OPERATING COST (per sample)

WATER		
WITH WATER COOLED RESISTOR 100@20¢/1000		2¢
WITHOUT WATER COOLED RESISTOR		0.04
ELECTRICITY		
PUMPING WATER TO 70 PSI		0.10
VACUUM PUMP		0.08
HEAT TREATING		
HEATING 2000A at 24V	15wh@1¢/kwh	0.01
HOLDING 50A at 24V	10wh@1¢/kwh	0.01
GRINDING		
TENSILE TESTING		
MISCELLANEOUS		
CONSUMABLES		
GAS (He/H_2 inert atmosphere) $43/330 cu. ft.		20.0
CHEMICAL POLISHING SOLUTION		10.0
GRINDING WHEELS		3.0
MOST SAMPLES		34¢
EARLY SAMPLES		36¢

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 1 COMPOSITIONS

Element	Sample				
	13267	18439	69427	54317	87180
C	0.10	0.06	0.12	0.07	0.115
P	0.013	0.008	0.005	0.05	
Mn	0.38	0.37	0.38	0.39	0.38
S	0.019	0.023	0.009	0.012	
Si	0.01	0.01	0.01		
Cu	0.08	0.11	0.04		
Ni	0.03	0.03	0.02		
Cr	0.01	0.01	TRACE		
Sn	0.01	0.01			
Mo	0.01	0.01	TRACE		
N_2	0.0035	0.01	0.003		
Cb			0.004		
V			0.005		
Al			TRACE		
As			0.004		

Table 2 CHEMICAL POLISHES

Solution	Composition
1	25% HF (48-50%) 10% HNO_3 65% H_2O
2	500 gms CrO_3 150 cc H_2SO_4 H_2O to make 1 litre
3	60 cc H_3PO_4 40 cc H_2O_2 (30%) 40 cc HF (48-50%)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3 DATA FOR FIGURE 11

Sample	UTS KSI	TIME SEC.
1	138	2.0
2	113	6.0
11	97	20.0
15	161	0.4
16	168	0.2
19	163	0.6
21	109	3.0
22	140	3.2
23	121	6.0
24	131	7.0

Table 4 DATA FOR FIGURES 12 & 13

Sample	UTS KSI	YS KSI	TIME SEC.
1	133	110	1
4	107	97	4
5	118	104	4.5
6	105	90	5
7	118	111	6
8	116	102	6
9	101	84	7
10	108	105	8
11	97	82	9
12	98	90	10
13	101	93	11
14	115	-	12
15	98	80	13
16	93	78	14
19	107	96	16
20	106	90	17
21	98	91	18
22	94	-	19
24	90	80	21
25	101	88	22
26	91	78	23
27	97	90	24
28	99	80	25
29	99	73	26
30	99	93	30

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5 DATA FOR FIGURES 14, 15, 16

SAMPLE	UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
52	159	124	3.0	3
53	152	105	2.9	1
55	150	147	0.8	$\frac{1}{4}$
57	175	157	1.3	3/4
58	158	146	1.5	2
59	164	127	3.0	$1\frac{1}{2}$
60	185	150	2.5	2
61	153	111	2.7	5
63	152	-	3.5	5
64	147	-	6.0	10
65	140	124	4.6	15
66	178	146	3.2	20
67	182	146	2.0	20
69	187	145	2.8	3
70	182	153	2.3	1
71	194	165	2.1	$\frac{1}{2}$
72	182	162	1.5	$\frac{1}{4}$
73	187	154	2.6	3/4
75	182	153	2.8	2
76	180	153	2.5	3
78	183	165	2.8	5
79	186	155	2.2	7

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6 — 975°C SAMPLE 69427

UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
156	130	1.3	32
160	136	1.8	30
160	140	2.4	45
161	136	1.7	30
134	125	1.0	30
129	118	1.1	30
138	120	1.7	24
142	123	1.7	21
152	128	1.7	21
148	120	2.6	23
148	123	1.5	14
153	131	1.7	12
176	139	3.4	1 1 1
169	135	2.7	1
183	150	3.5	1
176	144	2.8	1
187	154	1.8	½
167	135	2.5	1
156	134	3.0	.75
183	147	3.6	.7
186	139	4.5	.5
184	150	2.6	.7
201	168	4.0	.7
198	169	4.3	.4
196	163	3.0	.3
203	156	4.2	.25
202	158	4.0	.25
205	163	4.0	.4
194	155	3.7	.17
197	162	4.2	.15
183	151	2.7	.8
156	124	2.3	9
130	120	1.5	9
145	113	2.4	4
158	113	2.8	4
164	133	2.8	5
159	130	2.1	7.5
154	131	2.6	3
171	146	2.3	2
173	140	3.0	2
172	142	3.2	1.7
156	146	2.2	1.5
157	141	2.4	1.3
159	145	2.8	1.3
164	140	2.5	1.3
161	142	2.3	1.1
155	120	2.1	.9
176	140	3.7	1
182	144	2.8	1
167	140	2.9	1
185	155	3.3	.75
167	132	3.5	1.3

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7 925C SAMPLE 69427

UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
169	148	3.2	31
171	148	2.3	30
167	144	2.0	30
163	141	1.4	30
171	145	2.1	25
161	135	3.0	25
168	142	1.8	25
171	125	3.3	25
167	137	2.2	20
155	127	2.0	20
171	137	1.9	15
179	149	3.3	12
167	133	3.4	10
176	138	3.5	10
168	138	3.0	9
177	144	3.8	9
172	127	3.0	8
175	---	4.0	7
176	136	4.0	7
180	146	3.3	6
175	132	4.0	6
167	133	3.4	6
183	147	3.3	6
175	150	2.7	5
178	147	3.5	5
185	156	2.8	3
177	153	1.7	2.5
203	167	4.3	2.5
187	155	2.8	2
184	146	4.0	2
193	147	3.0	1.5
192	155	3.3	1.5
198	162	3.4	1.5
191	149	4.0	1.1
183	134	3.2	1
188	139	3.6	1
185	160	4.5	1
186	140	4.2	1
206	167	4.7	1
198	158	5.4	1
201	154	4.0	.75
183	148	2.2	.75
198	151	4.6	.75

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7 (Cont'd)

UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
185	150	3.2	0.6
199	153	3.4	0.5
200	152	4.8	0.4
193	154	4.0	0.4
195	153	5.2	0.4
186	---	4.5	0.3
194	156	4.0	0.25
197	150	5.0	0.2
192	151	4.0	0.15
185	154	3.5	0.1
198	148	5.3	0.08

Table 8 875C SAMPLE 69427

UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
170	137	1.6	55
187	164	2.2	40
165	122	2.0	35
165	124	1.9	27
177	143	2.0	20
183	146	2.4	20
177	129	2.6	14
178	129	3.0	10
167	120	3.7	4
180	134	3.4	4
166	135	2.2	3
168	135	4.0	.7
191	143	3.4	.5
166	130	3.1	.4
163	133	3.3	.4
188	130	5.0	.35
178	137	3.0	.3
187	130	4.3	.3
151	126	2.7	.3
197	152	4.2	.25
180	147	2.5	.2
184	127	3.7	.1
189	138	4.0	.09
181	171	2.7	.3

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 9 800C SAMPLE 69427

UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
137	110	2.2	1
148	82	8	1
145	108	5.5	1
161	115	3.7	1
145	103	1.8	30
170	143	1.3	30

Table 10 AS RECEIVED SAMPLE 69427

UTS KSI	YS KSI	ELONG. % in 1"
60	56	28
61	57	30
66	66	33

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 11 Tempering results Sample 69427
(Note: Each figure represents the average of 10 results)

Tempering Temperature	TIME min.	UTS KSI	YS KSI	ELONG. % in 1"
Room Temperature	120	195.4±4.0	162.8±3.5	4.3±0.6
	43,000	194.9±4.0	163.6±4.3	4.6±0.8
	90,000	199.6±10.7	163.7±3.6	4.4±0.4
100°C	10	193.5±2.8	160.0±2.1	4.7±0.7
	100	189.1±2.4	156.7±3.5	4.4±0.5
	1000	178.4±5.4	151.4±4.4	4.4±0.5
	10000	172.2±6.2	153.3±3.5	4.1±0.7
	50000	182.6±3.0	154.0±6.0	3.8±0.5
200°C	1	172.6±2.1	154.0±3.3	2.4±0.4
	10	165.5±4.1	146.3±8.2	2.3±0.7
	100	160.2±1.5	146.1±3.6	1.9±0.4
	1000	150.2±4.6	136.1±10.8	1.9±0.5
300°C	1	172.2±5.1	149.1±4.0	3.6±0.4
	10	162.2±3.1	145.4±4.6	2.5±0.7
	100	153.6±1.4	145.8±1.8	2.5±0.5
	1000	148.8±4.1	138.1±6.6	1.9±0.3

Table 12 Tempering results Sample 54317

Tempering Temperature	TIME min.	UTS KSI	YS KSI	ELONG. % in 1"
Room Temperature	48,000	159.9±5.9	138.8±6.2	3.1±0.7
100°C	100	154.2±4.7	137.6±6.0	3.2±0.7
	10000	153.8±1.9	134.5±3.2	3.7±0.4
	30000	149.4±9.1	132.2±6.1	2.5±0.4
	50000	152.2±2.8	136.3±2.8	2.9±0.3
200°C	100	139.9±2.8	131.2±2.8	2.7±0.3
300°C	100	141.2±13.0	130.8±11.2	1.8±0.5

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE 13 DATA FOR FIGURES 26,27,28.

SAMPLE	UTS KSI	YS KSI	ELONG. % in 1"	TIME SEC.
1	178	146	2.0	.5
4	200	162	3.0	.5
5	190	160	3.0	.5
6	184	166	1.3	.5
7	191	170	3.2	.5
8	190	158	1.7	1
9	187	157	2.3	2
10	180	160	2.1	3
11	176	143	3.0	3.5
12	183	145	2.5	4
13	178	140	2.8	5
14	178	148	2.1	5
15	177	143	2.5	5
16	175	145	1.8	5
18	185	143	2.5	5
19	180	137	2.6	5
20	179	146	2.4	5
21	191	159	3.2	.5
22	189	162	2.4	.75
24	182	169	1.9	5
25	175	143	1.5	5
26	180	167	1.8	10
27	170	132	2.7	10
29	173	-	1.0	10
30	181	146	2.1	10
31	174	141	2.3	5
32	182	151	1.8	5
33	189	166	1.8	5
34	121	98.5	9.7	20
35	130	82	7.1	15
37	105	75	5.8	30
38	163	134	1.7	15
39	180	149	2.3	10
40	180	147	2.3	10
41	182	155	2.6	5
44	150	121	1.4	15
45	156	113	4.3	30
46	147	137	5.8	10
47	165	141	1.6	20
48	180	158	1.7	5
49	151	138	1.6	25
50	178	145	2.7	5

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 14 .45 Sec. SAMPLE 54317

Temperature °C	UTS KSI	YS KSI	ELONG. % in 1"
780	114	74.5	8.7
785	96	59	9.6
800	96	67	8.1
810	105	73	8.0
815	107	71	10.1
830	118	78	8.0
835	118	86	7.6
835	126	91	5.0
840	117	102	2.0
850	112	100	4.5
850	116	89	5.0
855	145	116	5.6
860	131	119	2.8
865	158	137	3.3
870	160	136	4.5
875	162	131	4.0
875	136	103	4.6
880	127	109	4.0
890	136	118	2.8
890	125	109	3.5
895	128	93	4.8
900	161	142	4.2
910	165	146	3.6
915	162	141	2.6
920	161	141	3.0
925	158	137	3.3
930	171	153	4.0
930	164	138	3.5
955	152	136	2.8
960	152	136	2.7
960	166	138	4.6
970	167	141	4.6
970	156	132	3.2
970	168	140	5.5
1000	150	130	4.0
1010	157	139	3.0
1010	171	149	4.2
1050	161	135	5.0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 15 30 Sec. SAMPLE 54317

Temperature °C	UTS KSI	YS KSI	ELONG. % in 1"
760	99	52	6.5
770	108	71	2.9
790	106	59	10.1
800	124	85	4.3
805	106	67	9.7
820	107	60	8.0
830	126	83	5.4
840	100	56	8.8
850	141	116	1.7
850	119	75	6.8
860	158	122	3.0
870	147	115	3.0
875	159	121	3.7
890	124	100	2.8
900	151	123	4.0
915	155	124	3.2
930	150	118	3.1
930	129	92	2.9
930	136	121	1.4
950	141	---	2.5
960	125	95	2.6
990	138	110	2.0
1050	144	132	2.8
1090	121	93	2.0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 16 950°C Sample 54317

TIME SEC.	UTS KSI	YS KSI	ELONG. % in 1"
.15	166	138	4.8
.25	172	151	4.6
.5	154	129	4.1
.5	162	136	3.1
.5	158	133	3.4
1	143	115	4.0
1	160	134	3.6
1	165	138	5.0
2	159	132	3.4
2	166	138	4.0
2	168	138	4.4
4	145	125	3.5
4	149	128	3.7
4	155	---	4.0
4	145	119	4.0
8	149	128	4.5
8	143	117	3.2
8	148	117	4.5
16	123	100	2.3
16	144	120	4.0
16	152	117	3.9
16	150	124	2.0
16	152	126	2.8
16	153	128	3.3
30	116	78	2.2
30	143	119	3.0
30	131	122	1.6
40	152	137	3.5
40	145	127	3.5
50	167	137	3.9
50	168	139	3.5
50	163	140	3.3
60	155	133	2.0
60	131	118	1.1
70	122	116	0.8
70	136	116	1.7
70	109	107	0.9
80	136	128	0.9
80	151	140	1.5
90	119	105	1.3
90	118	113	1.0
165	131	114	2.0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 17 Cold Worked SAMPLE 87180

Temperature °C	TIME SEC.	UTS KSI	YS KSI	ELONG. % in 1"
875	0.12	130	110	2.0
875	0.12	120	87	4.0
875	0.12	132	109	5.5
875	0.12	102	84	2.3
875	0.12	134	112	2.2
875	0.3	123	109	3.2
875	0.3	121	92	3.2
875	0.3	152	121	3.7
875	0.3	127	97	3.7
875	0.3	137	100	4.8
875	0.3	155	112	6.7
875	0.3	133	111	4.0
875	0.7	154	122	4.0
875	0.7	141	100	3.4
875	0.7	142	111	3.6
875	0.7	141	116	3.4
875	0.7	151	120	3.5
875	1.5	134	108	3.2
875	1.5	134	115	3.5
935	0.12	181	160	3.5
935	0.12	168	147	2.5
935	0.12	169	121	4.6
935	0.12	161	117	3.2
935	0.12	164	136	3.3
935	0.12	169	123	3.8
935	0.12	166	111	3.9
935	0.3	173	129	3.6
935	0.3	159	126	3.0
935	0.3	175	130	4.0
935	0.3	160	137	3.6
935	0.3	166	132	4.0
935	0.3	138	123	3.1
935	0.3	140	118	3.3
935	0.3	162	133	3.0
935	0.7	165	137	2.9
935	0.7	168	132	4.0
935	0.7	160	127	3.9
935	0.7	142	113	5.2
935	0.7	174	147	4.3
935	1.5	157	126	4.0
935	1.5	141	110	4.1
935	1.5	167	126	5.5
935	1.5	137	118	3.2
935	1.5	162	128	4.1
935	1.5	111	87	5.0
935	1.5	185	124	3.5
935	1.5	130	112	1.7

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE 18 IMPACT TESTS

AS RECEIVED	16.0 ft. lbs.
NORMALIZED	25.7 ft. lbs.
150 C	15.1 ft. lbs.
27 C	14.3 ft. lbs.
-20 C	15.3 ft. lbs.
-70 C	8.5 ft. lbs.

TABLE 19 X-RAY LINE WIDTHS*

SAMPLE	TREATMENT	LINE	WIDTH (°)
59	1 Sec. 910 C	110	.320
		200	.415
		211	.565
73	25 Sec. 920 C	110	.443
		200	.830
		211	.910
96	30 Sec. 950 C	110	.467
		200	.762
		211	.905
139	.15sec. 950 C	110	.318
		200	.695
		211	.762
150	4 Sec. 900 C	110	.438
		200	.667
		211	.762
227	½ Sec. 950 C	110	.390
	200 C 10 Min.	200	.523
		211	.619

* Width half way between peak and background

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

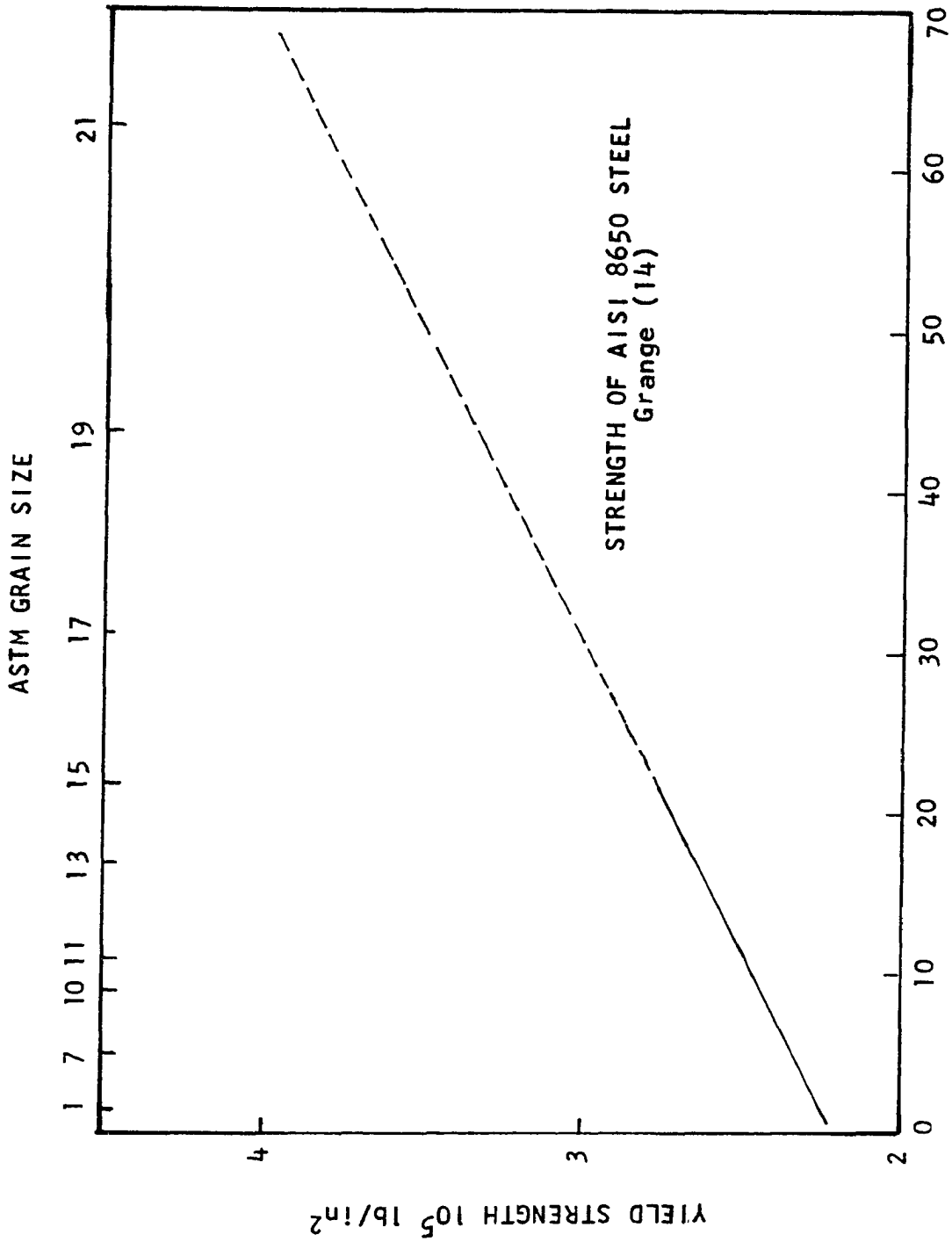


Figure 1

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

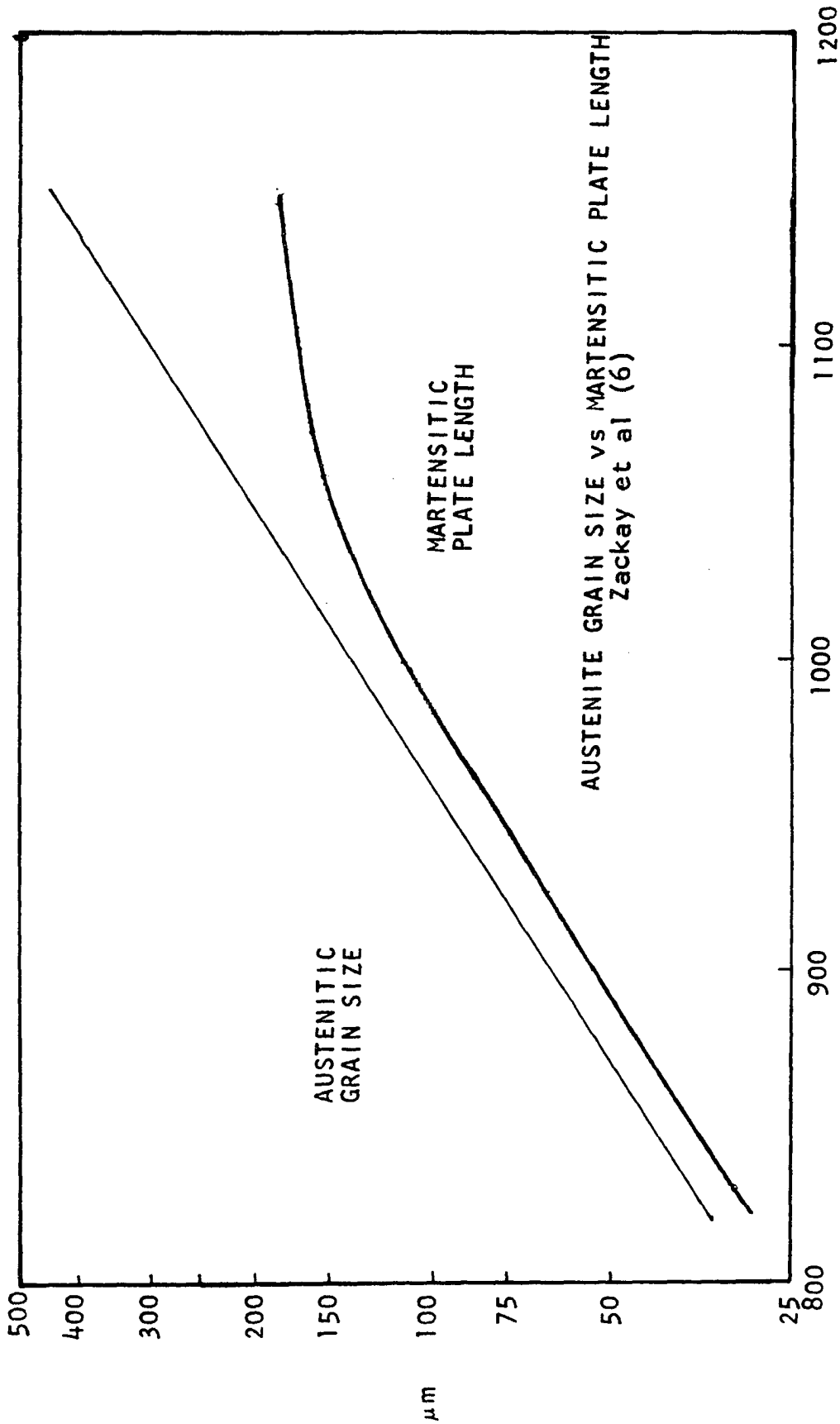


Figure 2

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

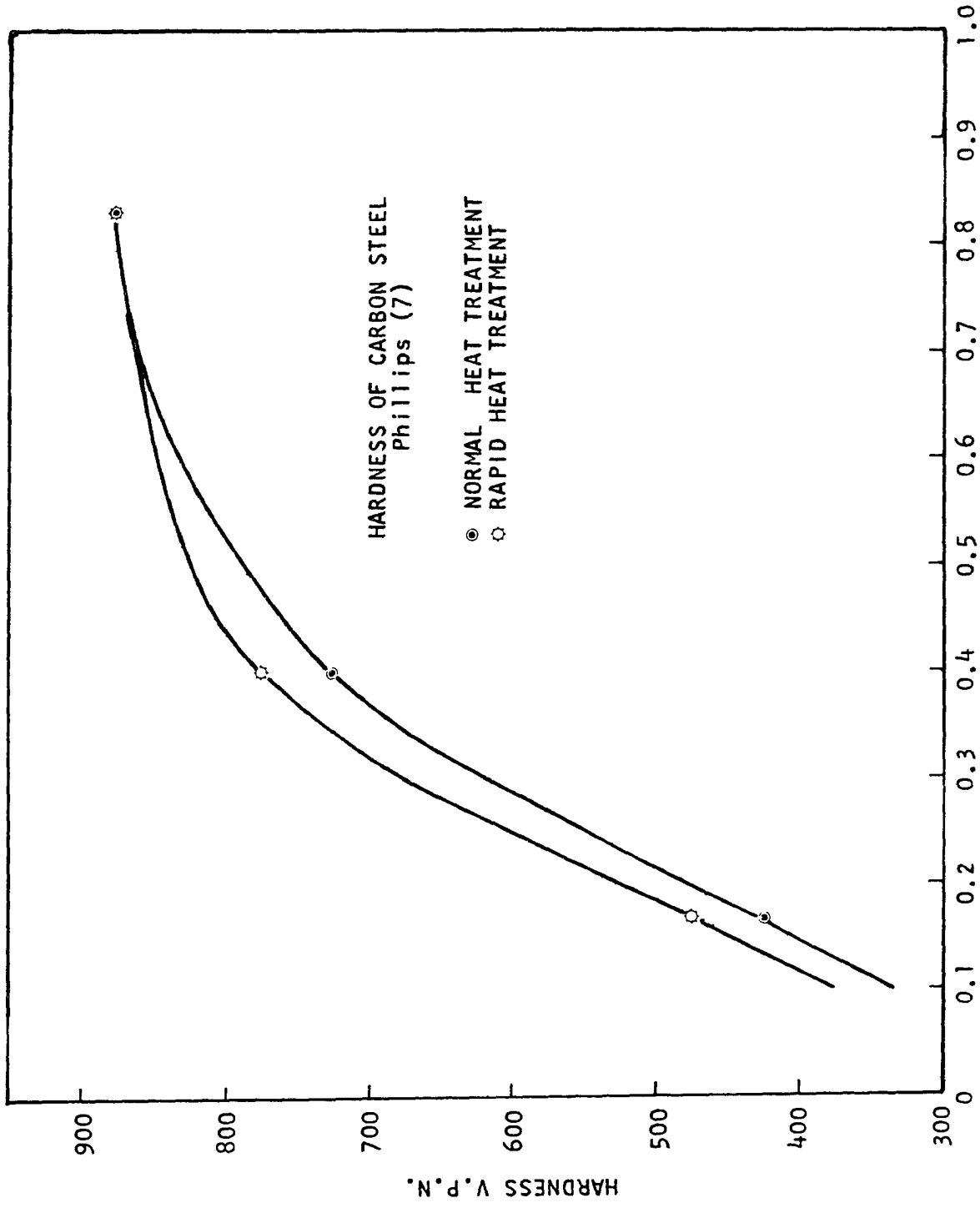
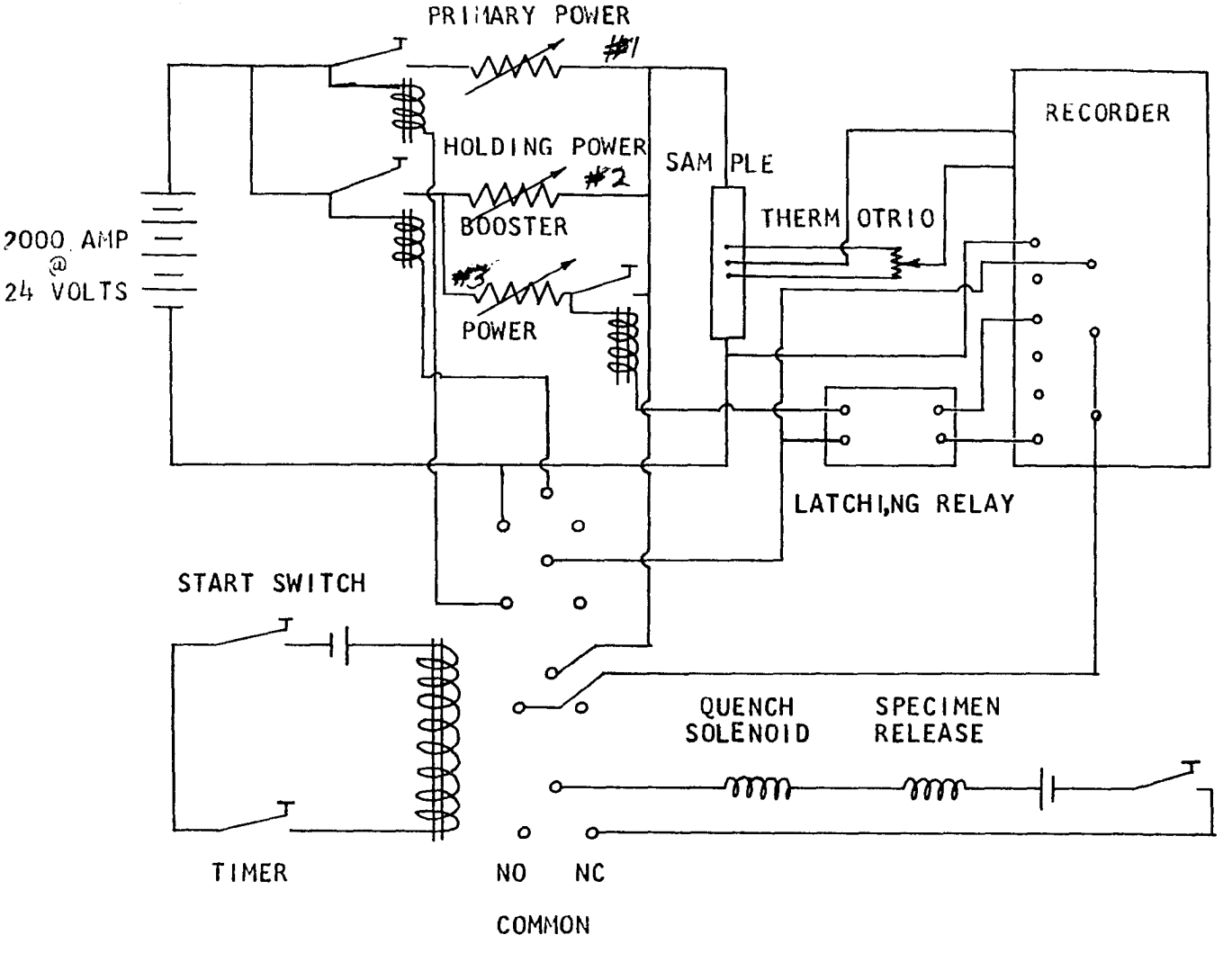


Figure 3

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.



CIRCUIT DIAGRAM OF QUENCH APPARATUS

Figure 4

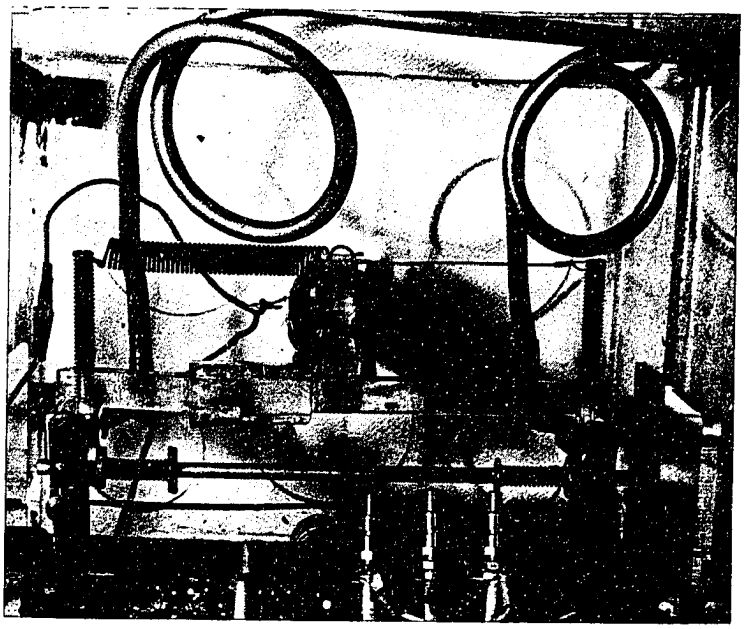


Figure 5 QUENCH APPARATUS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

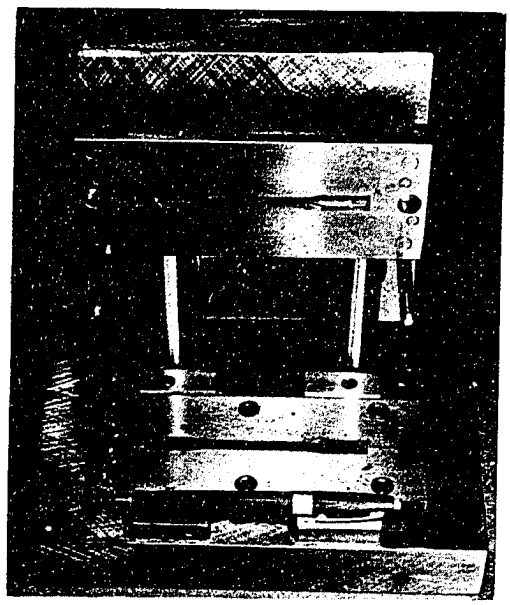


Figure 6 TENSILE SPECIMEN PUNCH

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

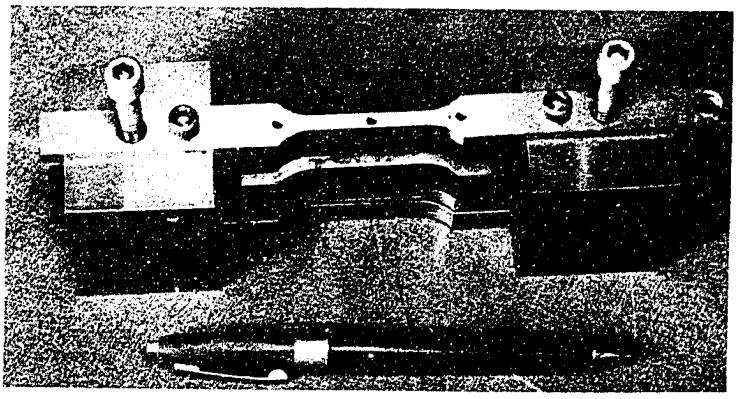


Figure 7 TENSILE GRIND FIXTURE

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

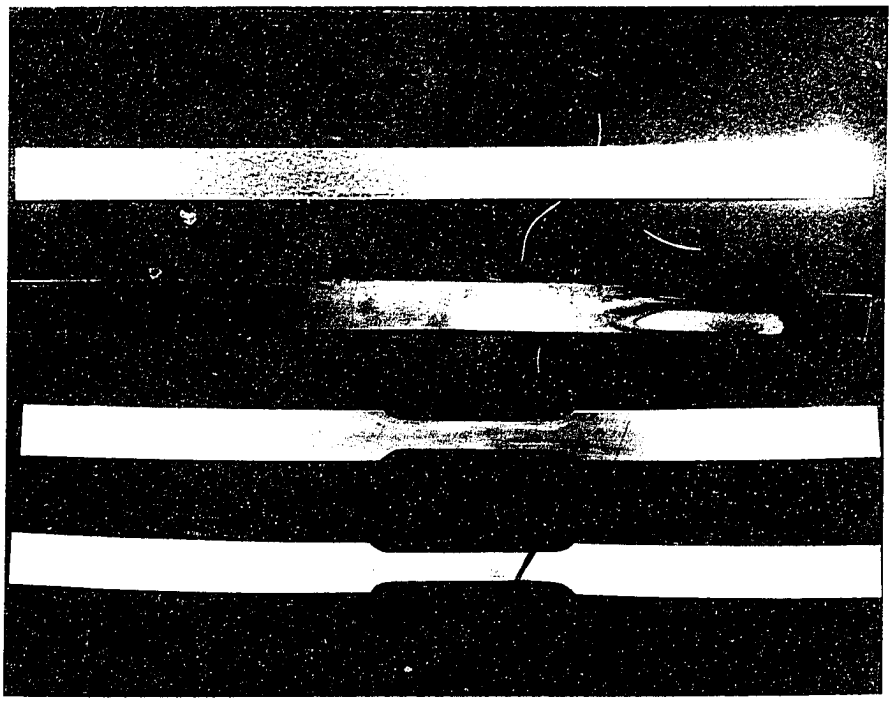


Figure 8 TENSILE SPECIMENS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

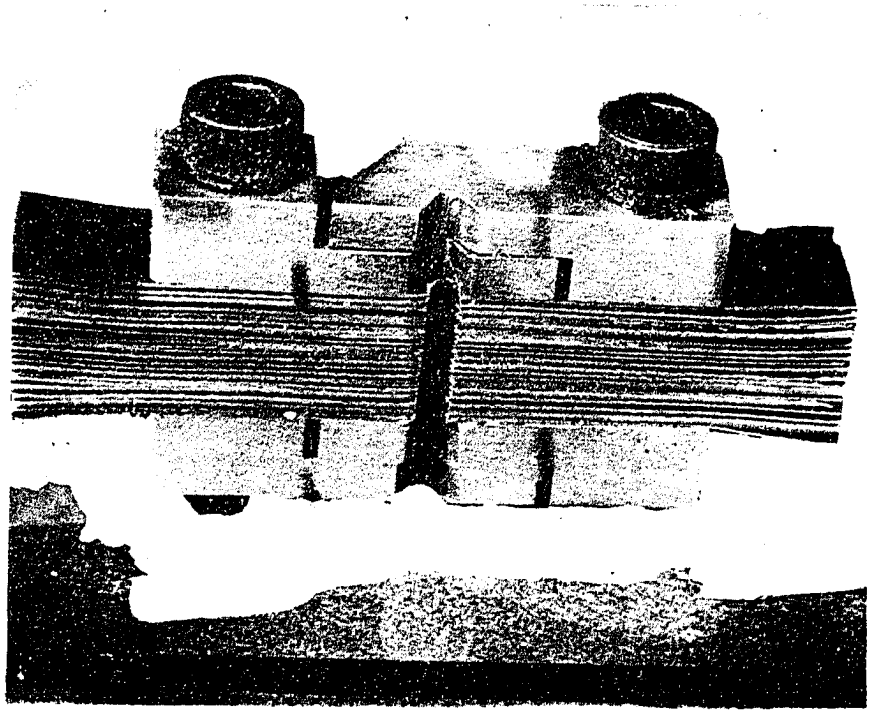


Figure 9 IMPACT SAMPLE

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

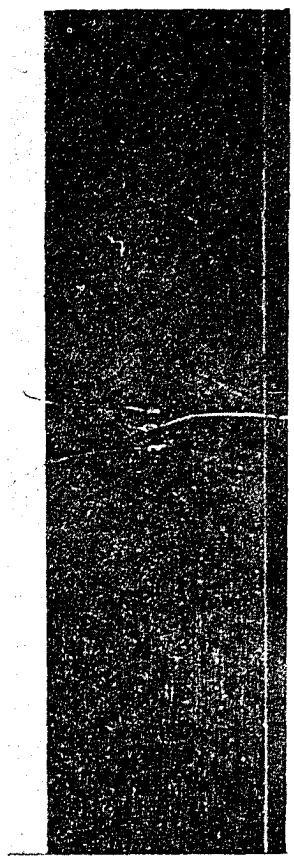


Figure 10 THERMOTRIO

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

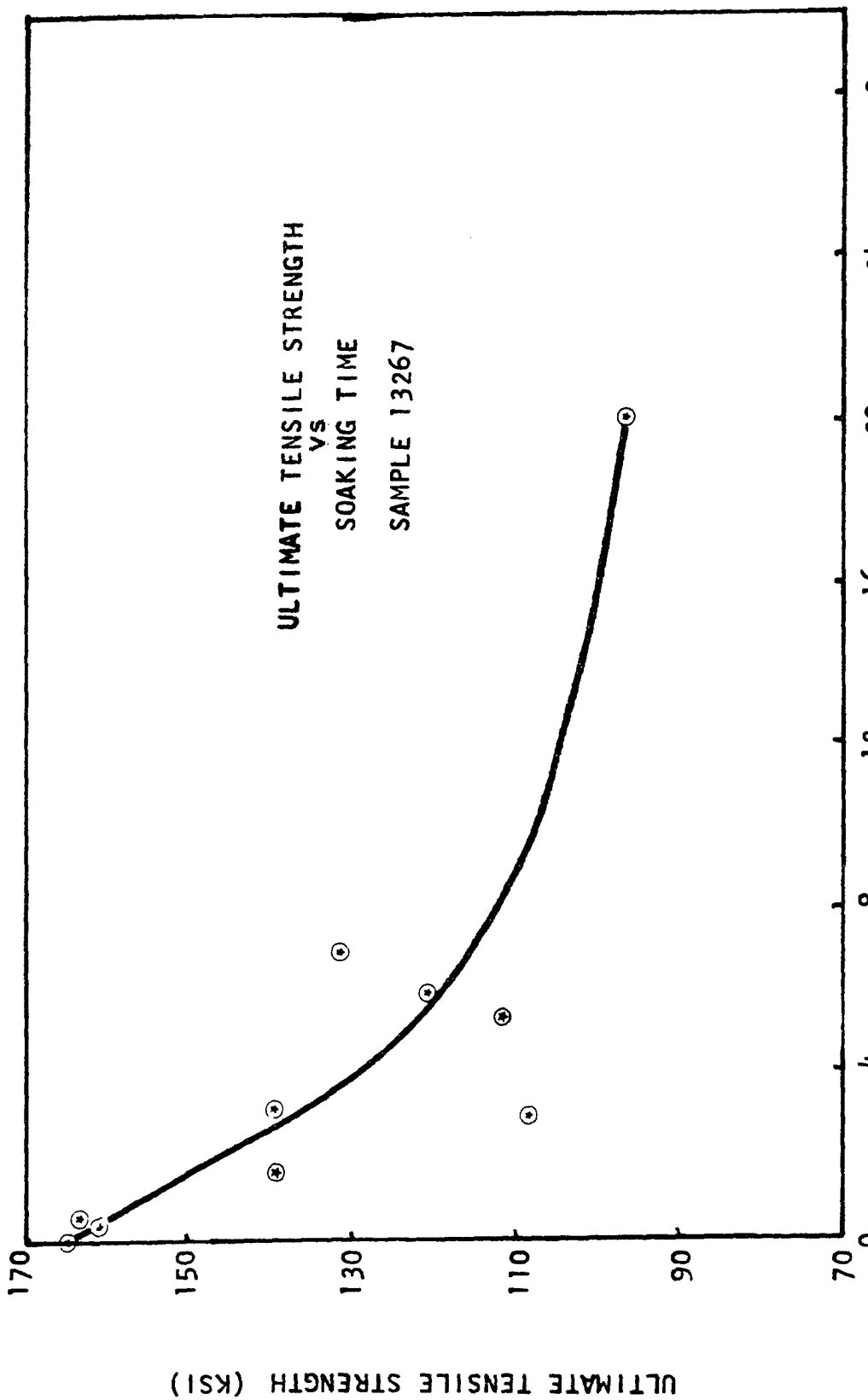


Figure 11

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

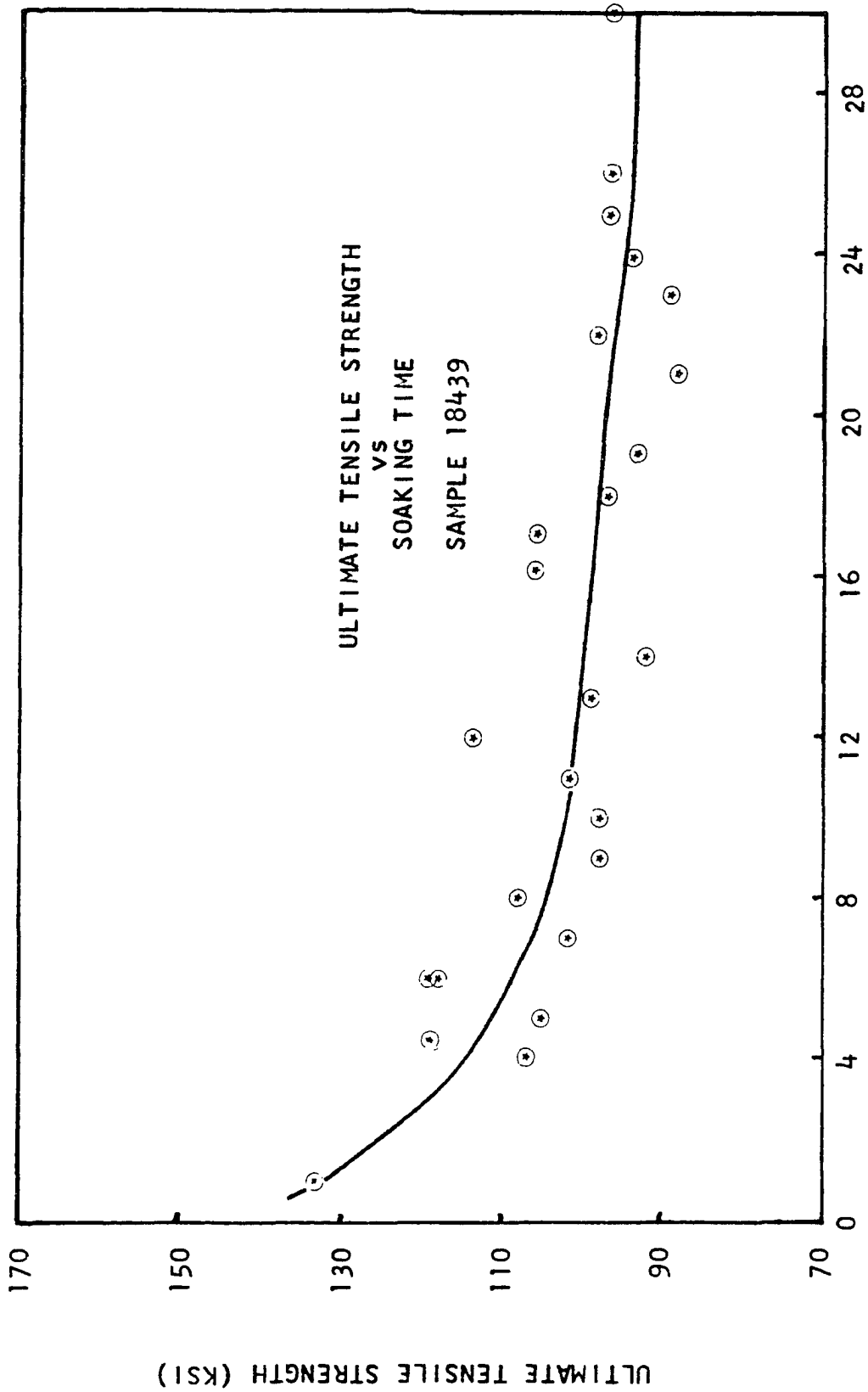


Figure 12

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UNIVERSITY OF WINDSOR LIBRARY

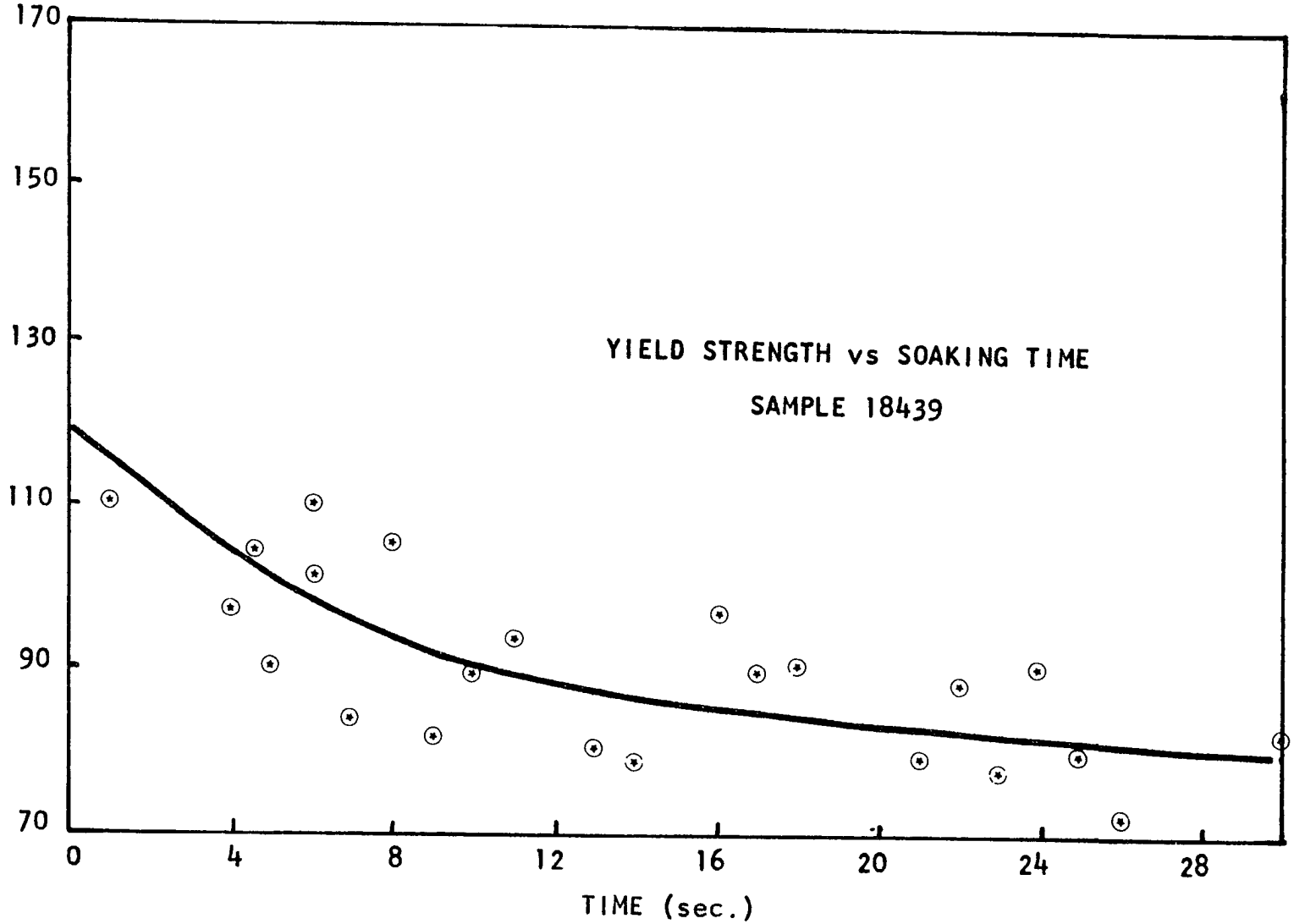


Figure 13

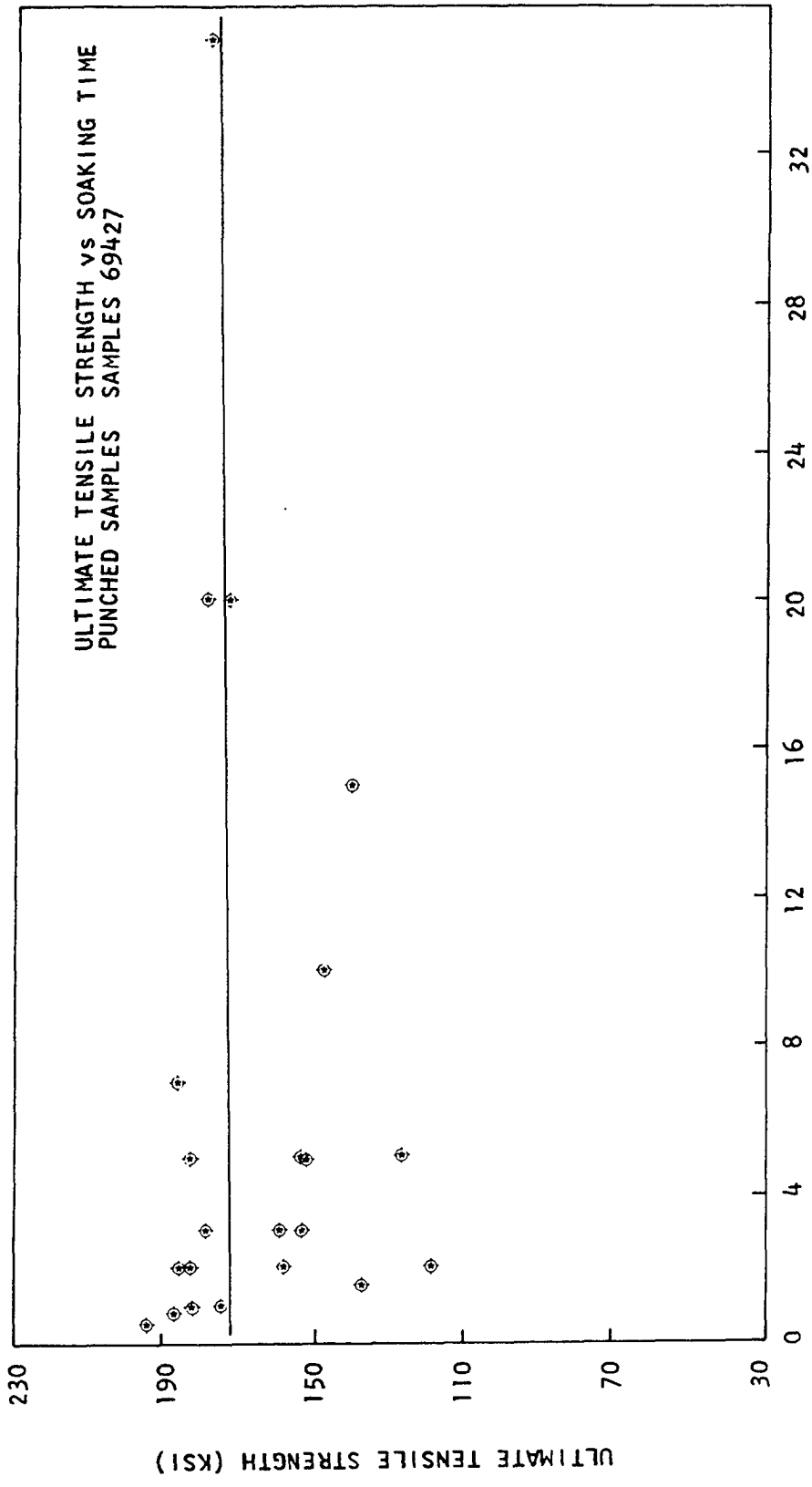


Figure 14

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

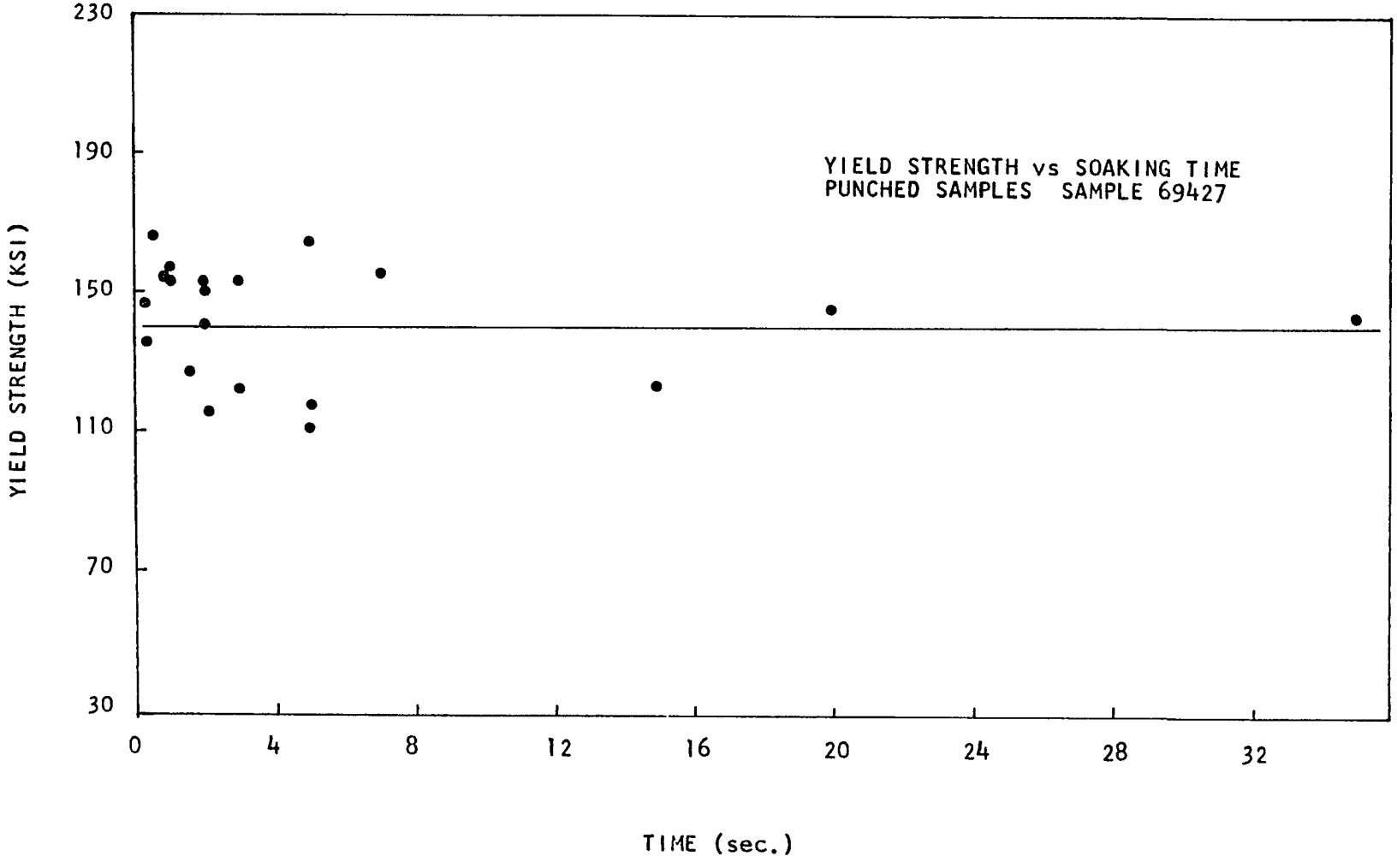


Figure 15

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

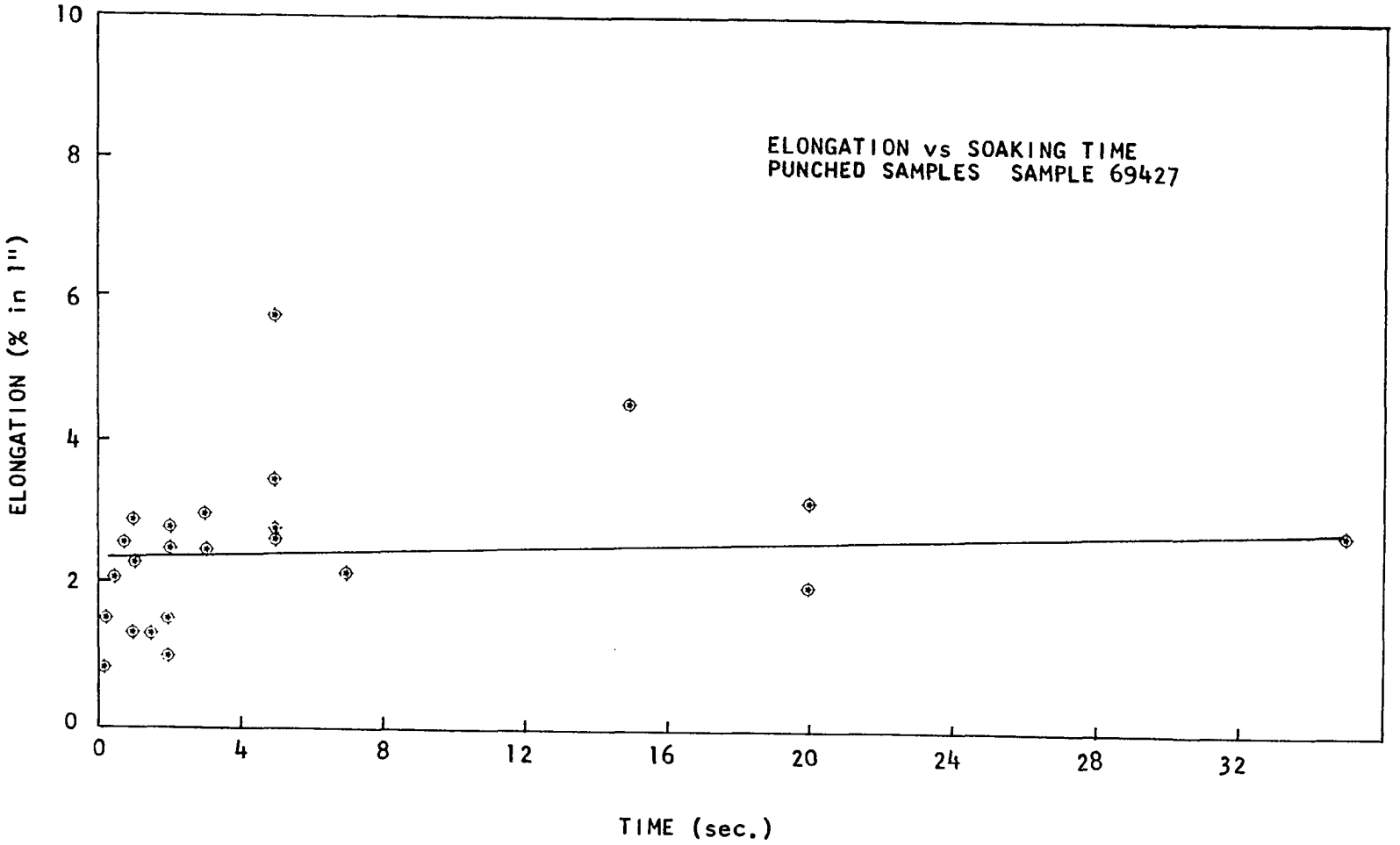


Figure 16

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

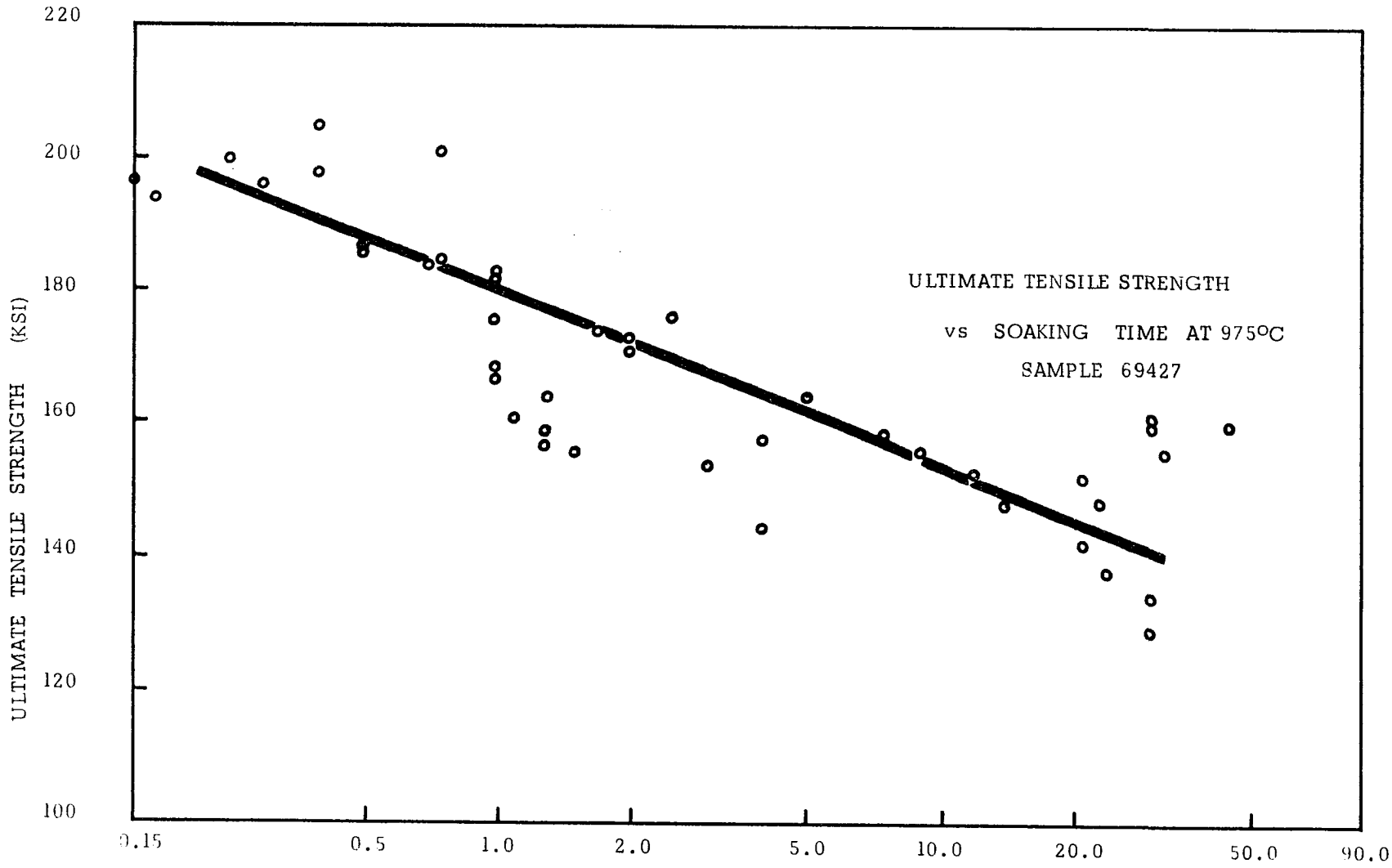


FIGURE 17

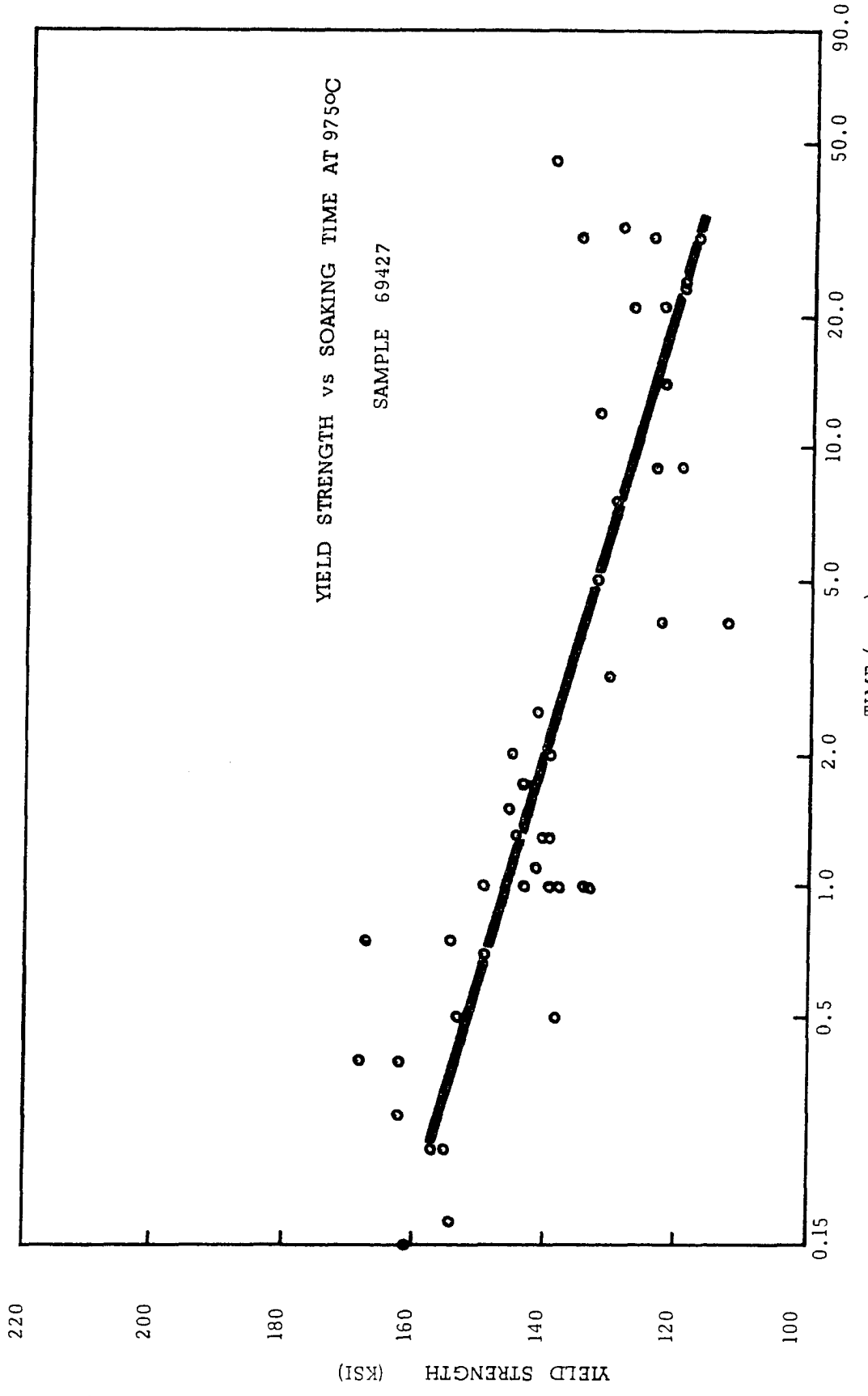


FIGURE 18

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

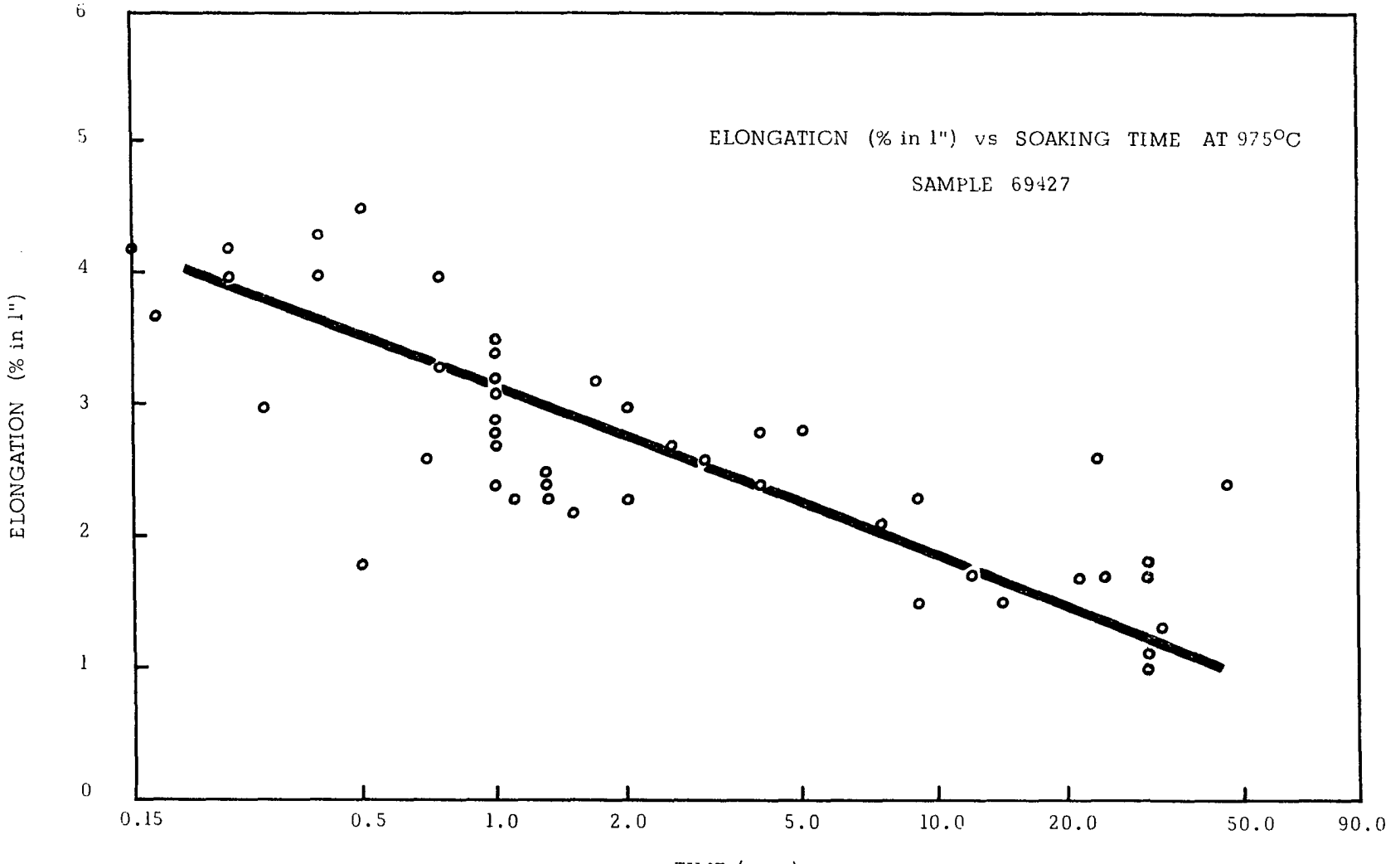


FIGURE 19

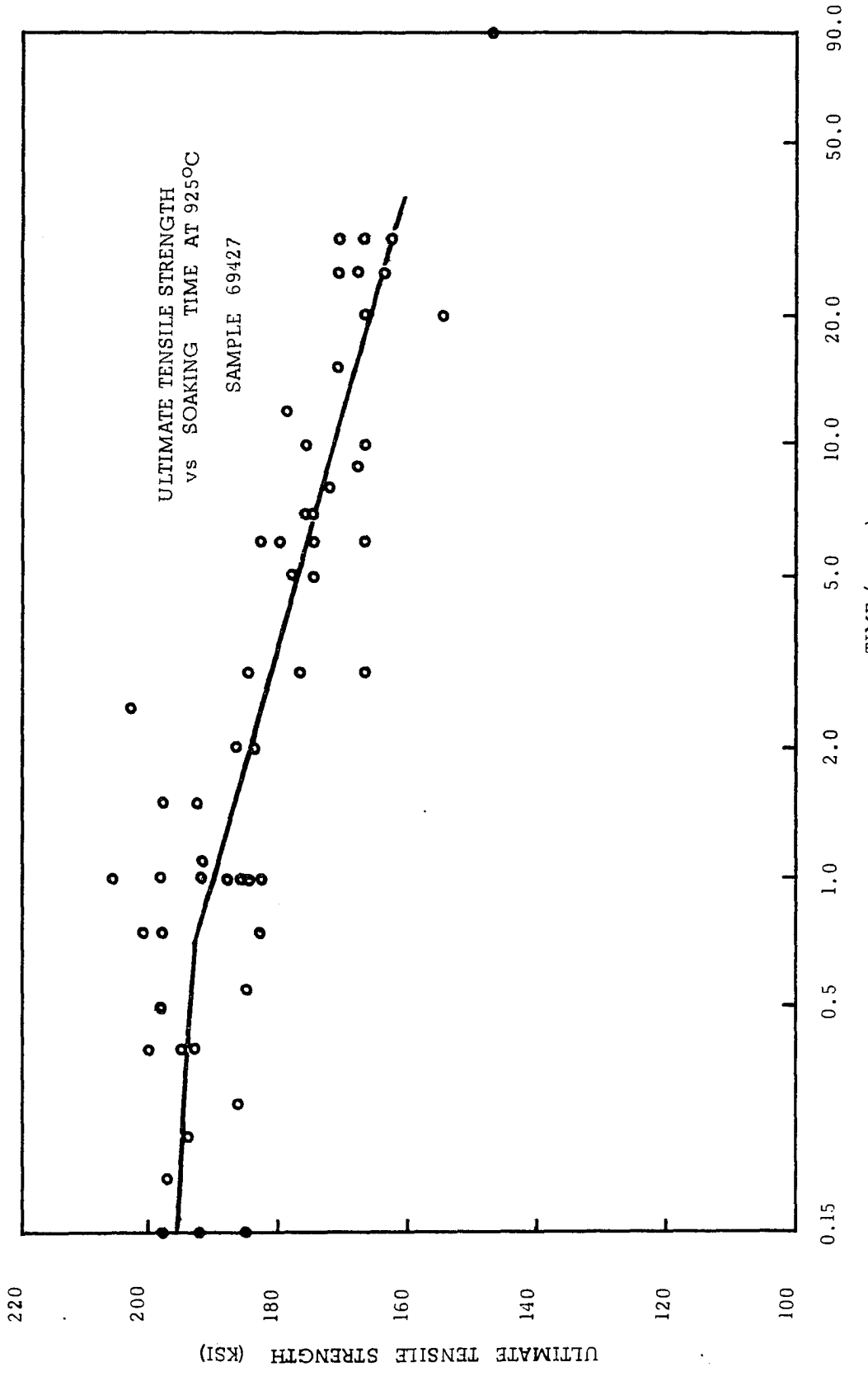


FIGURE 20

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

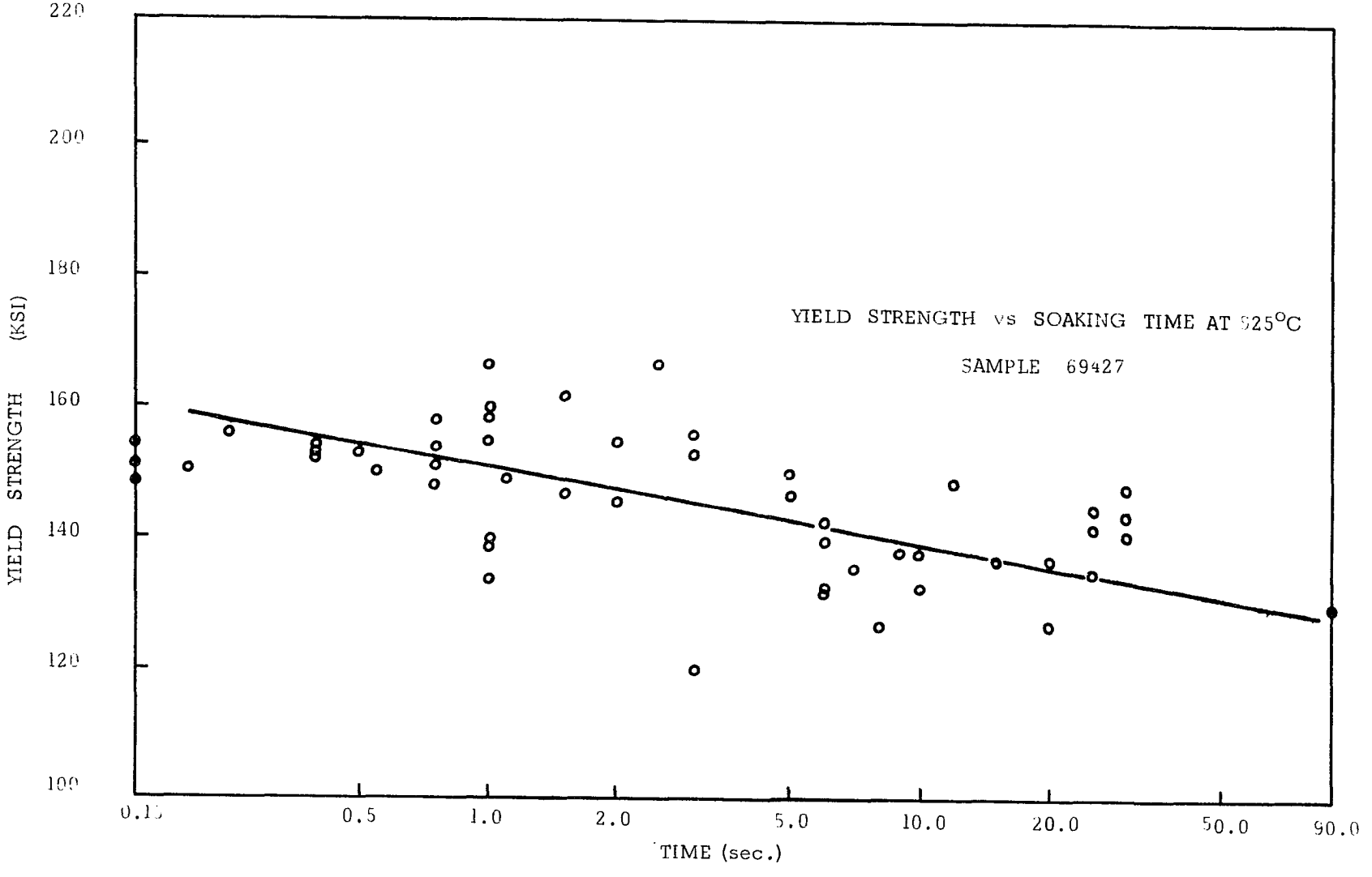


FIGURE 21

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

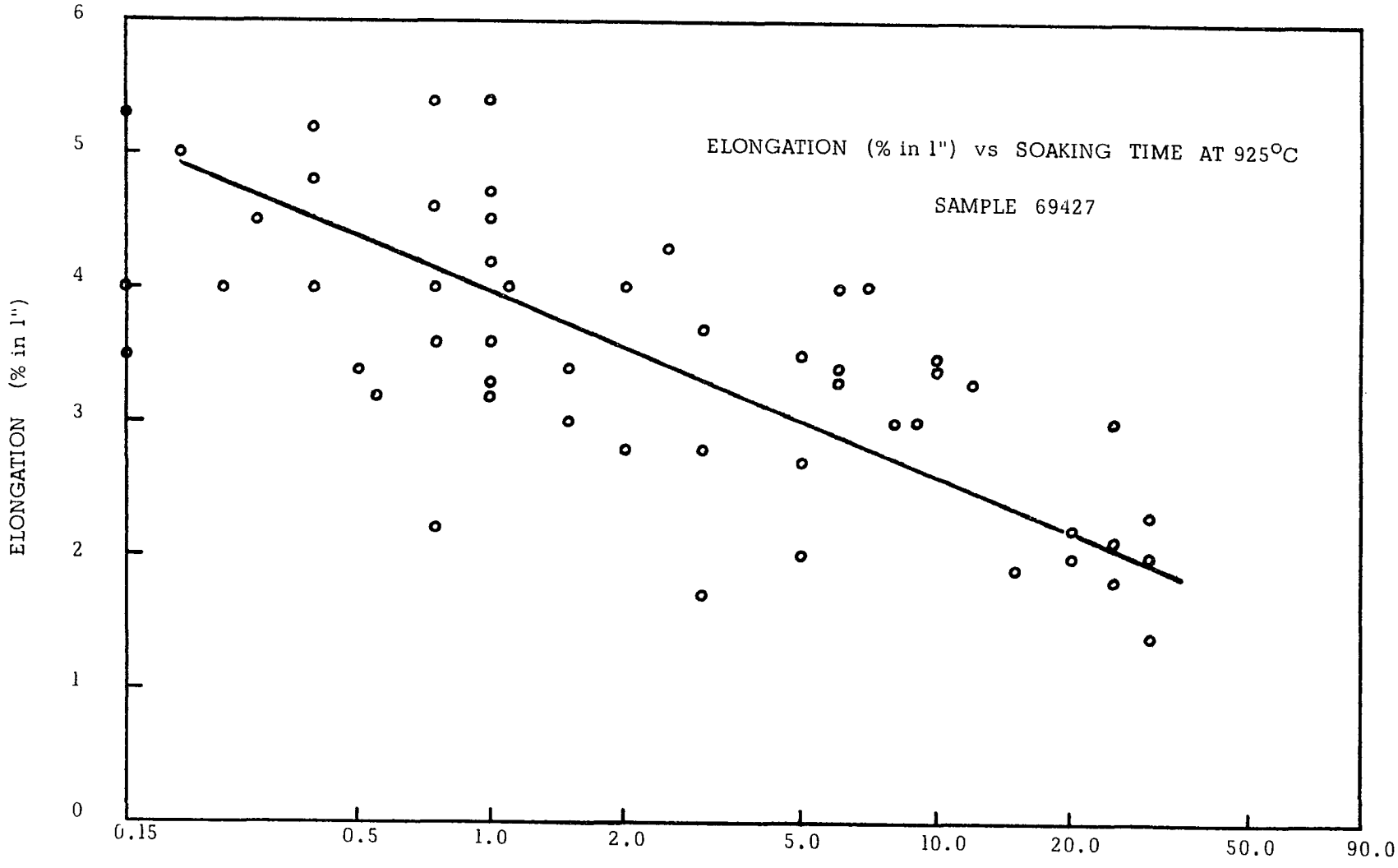


FIGURE 22

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

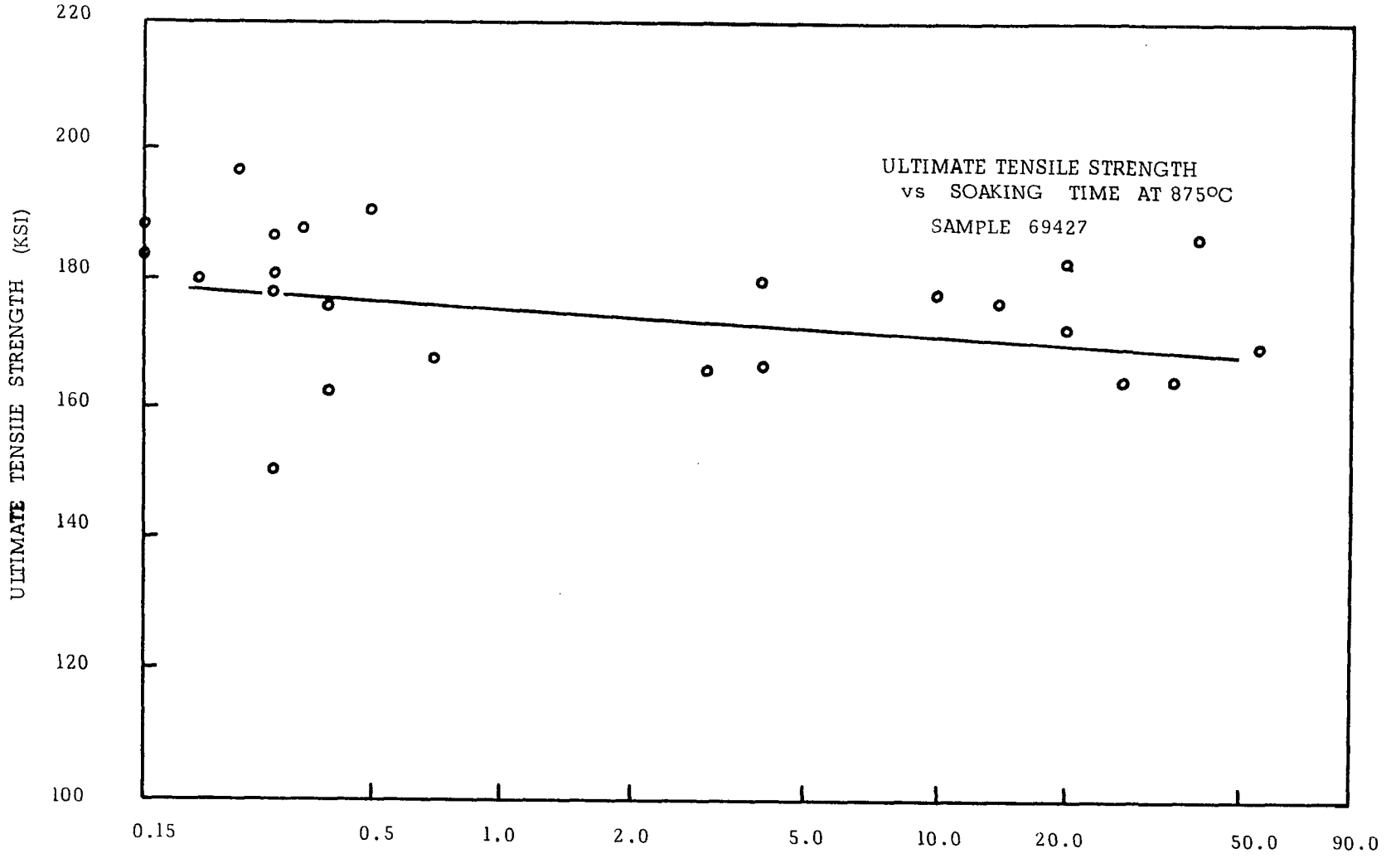


FIGURE 23

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

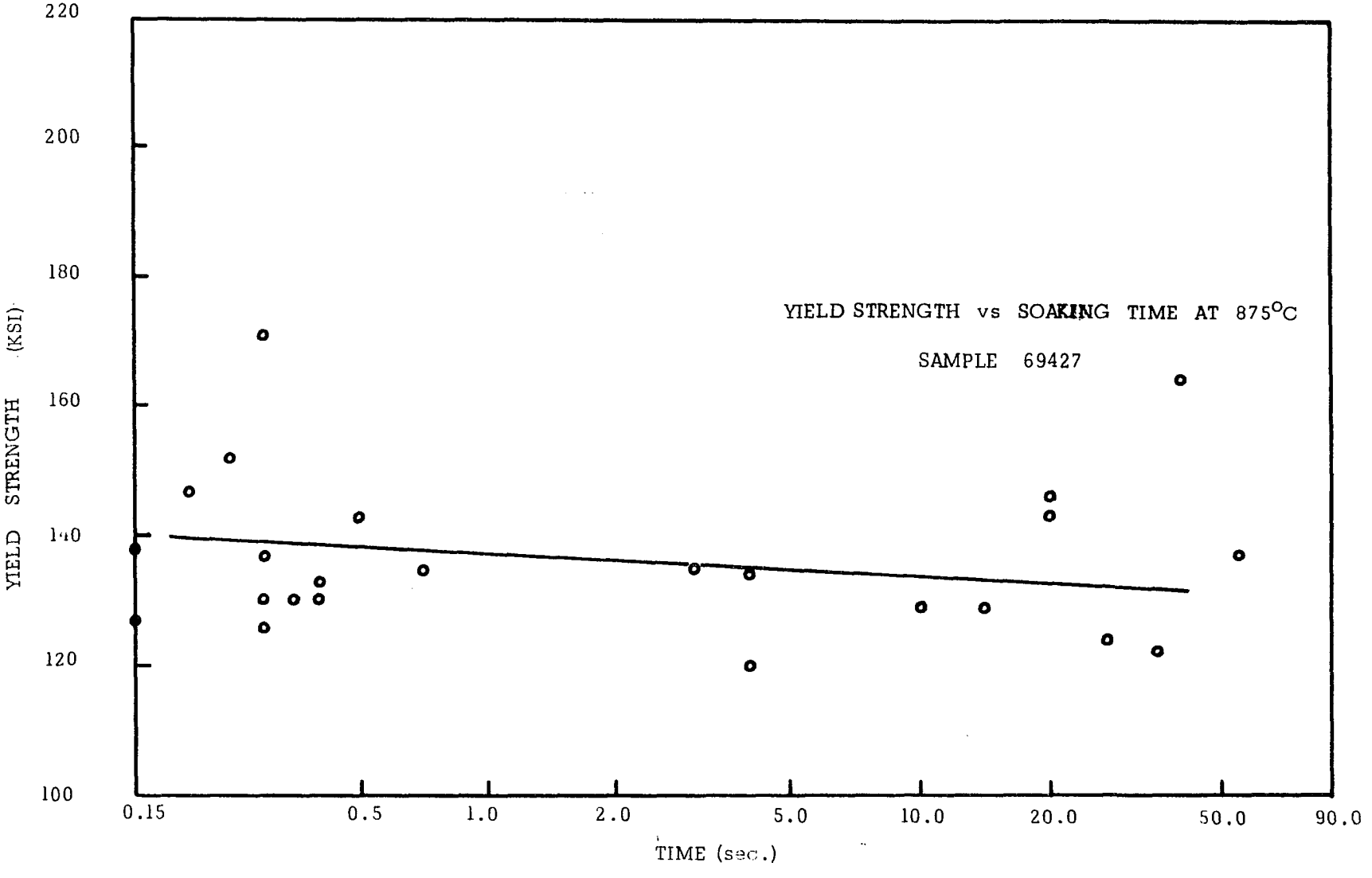
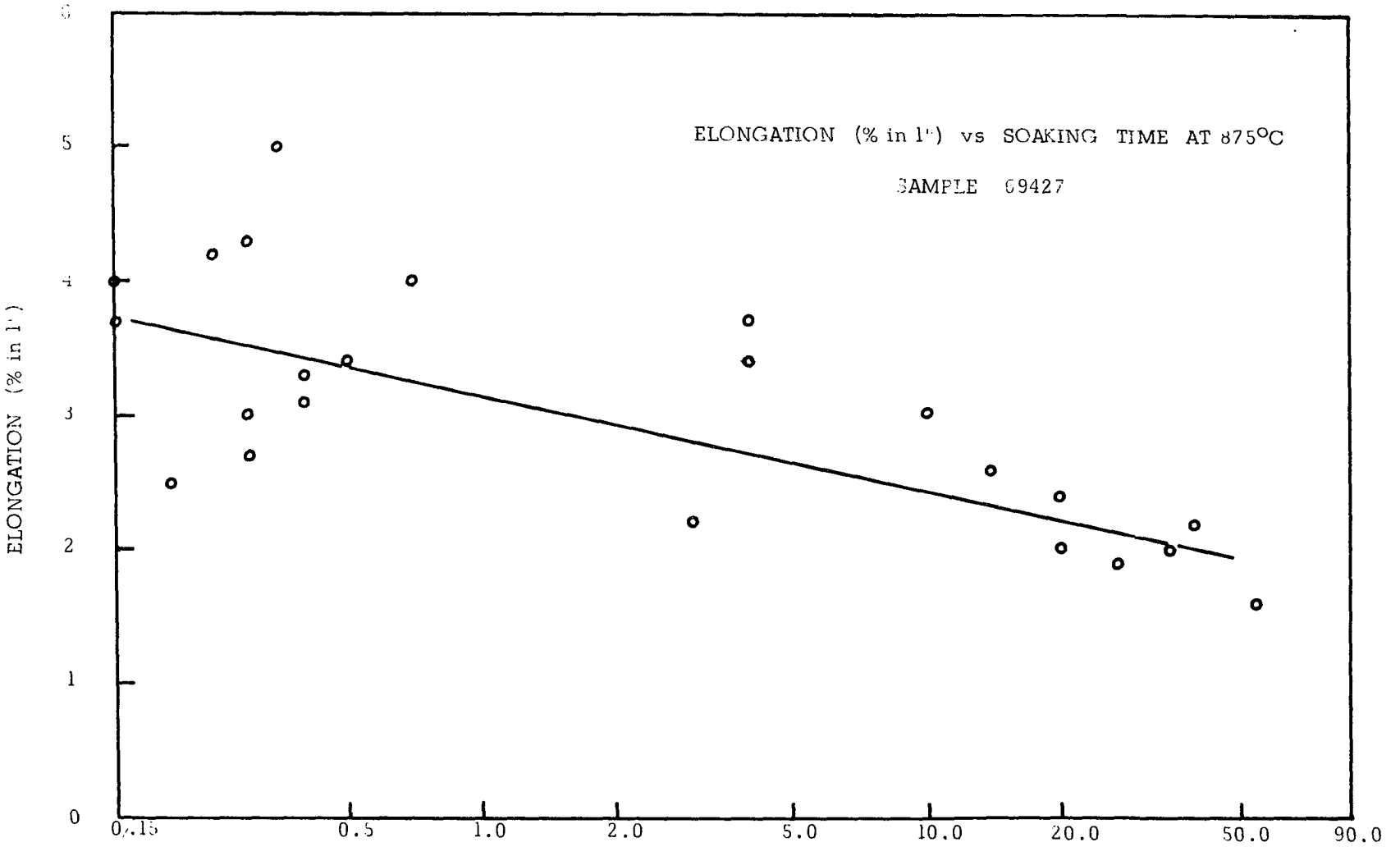


FIGURE 24

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.



ELONGATION (% in 1") vs SOAKING TIME AT 875°C

SAMPLE 69427

FIGURE 25

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

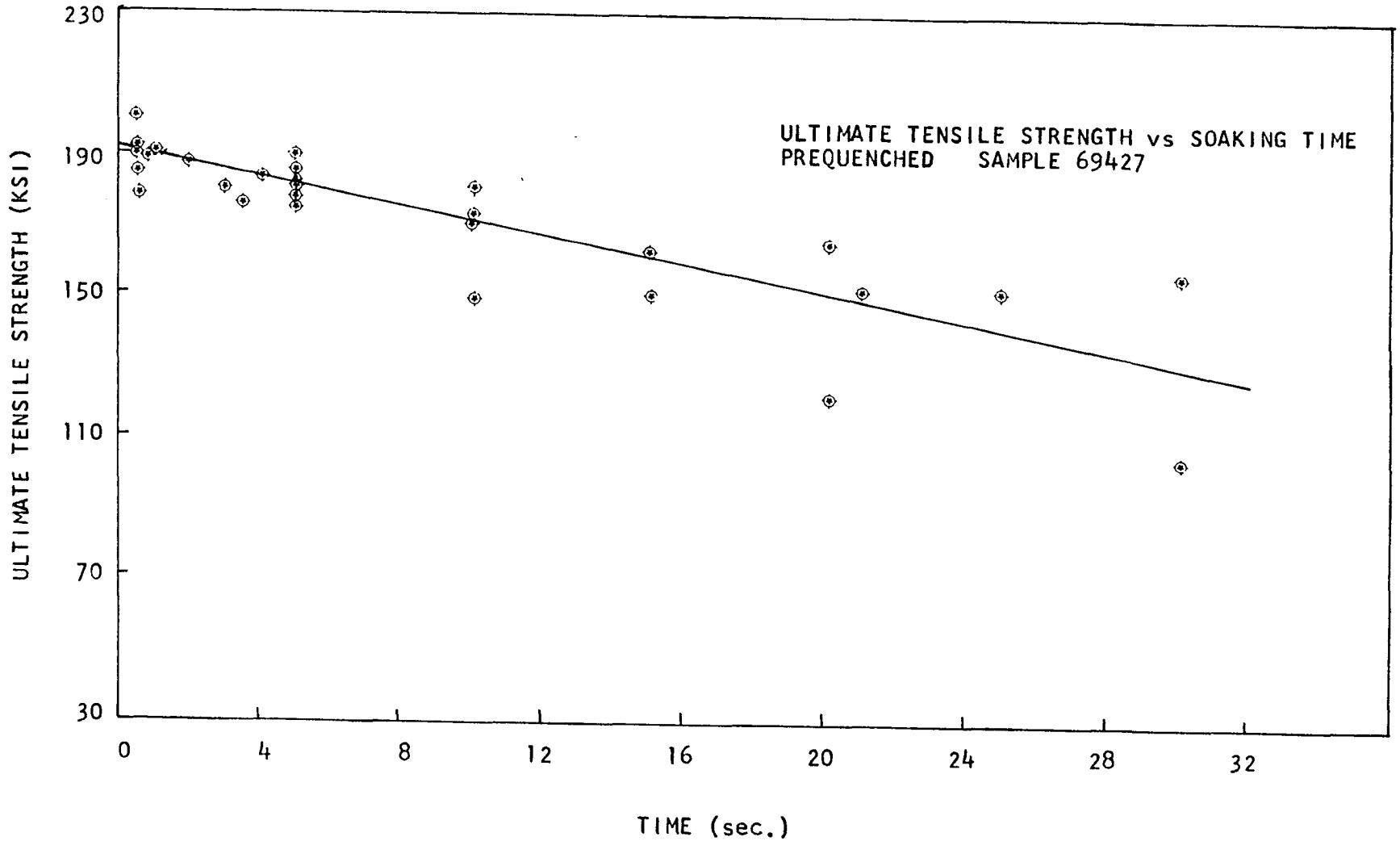


Figure 26

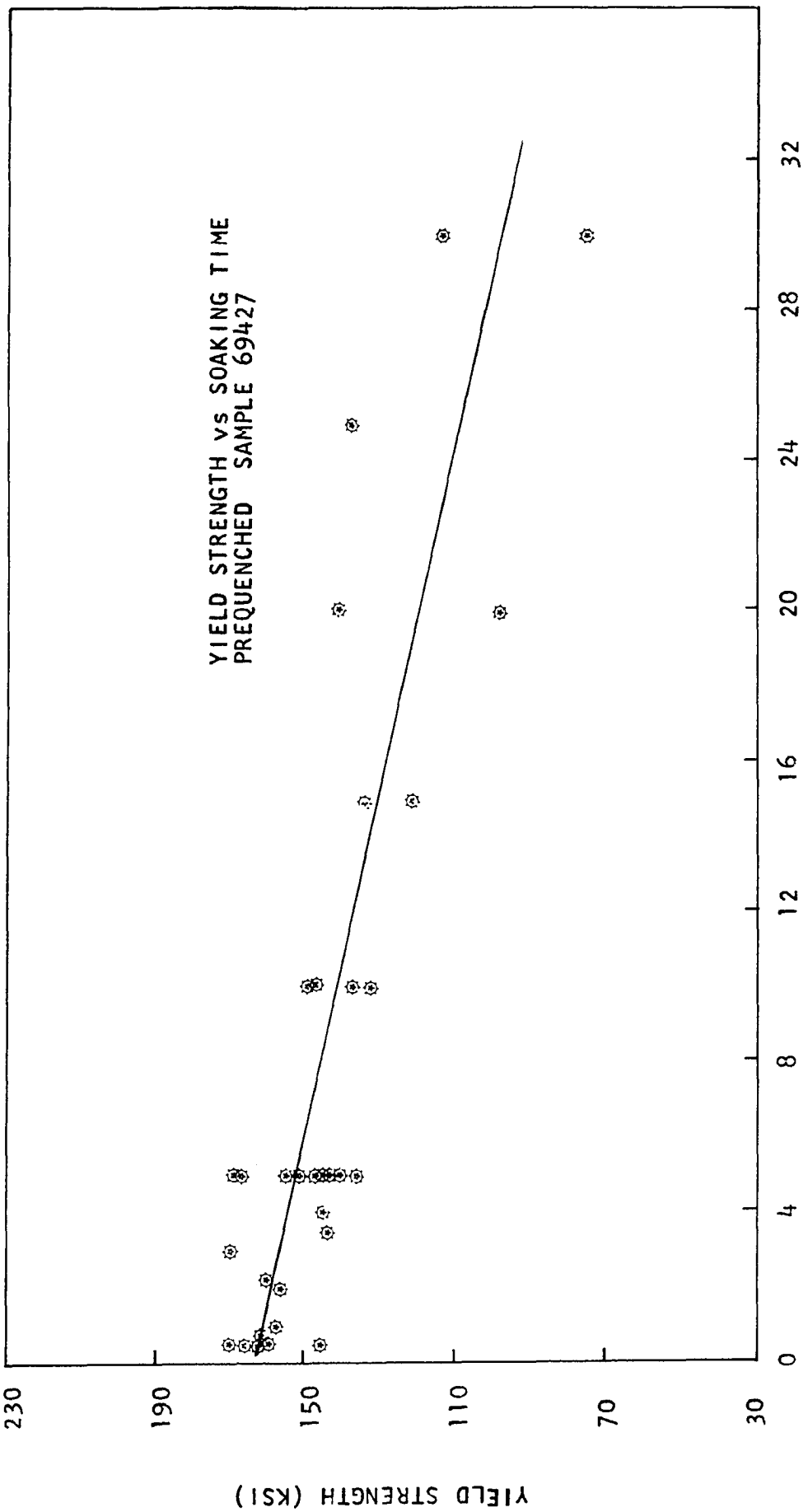


Figure 27

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

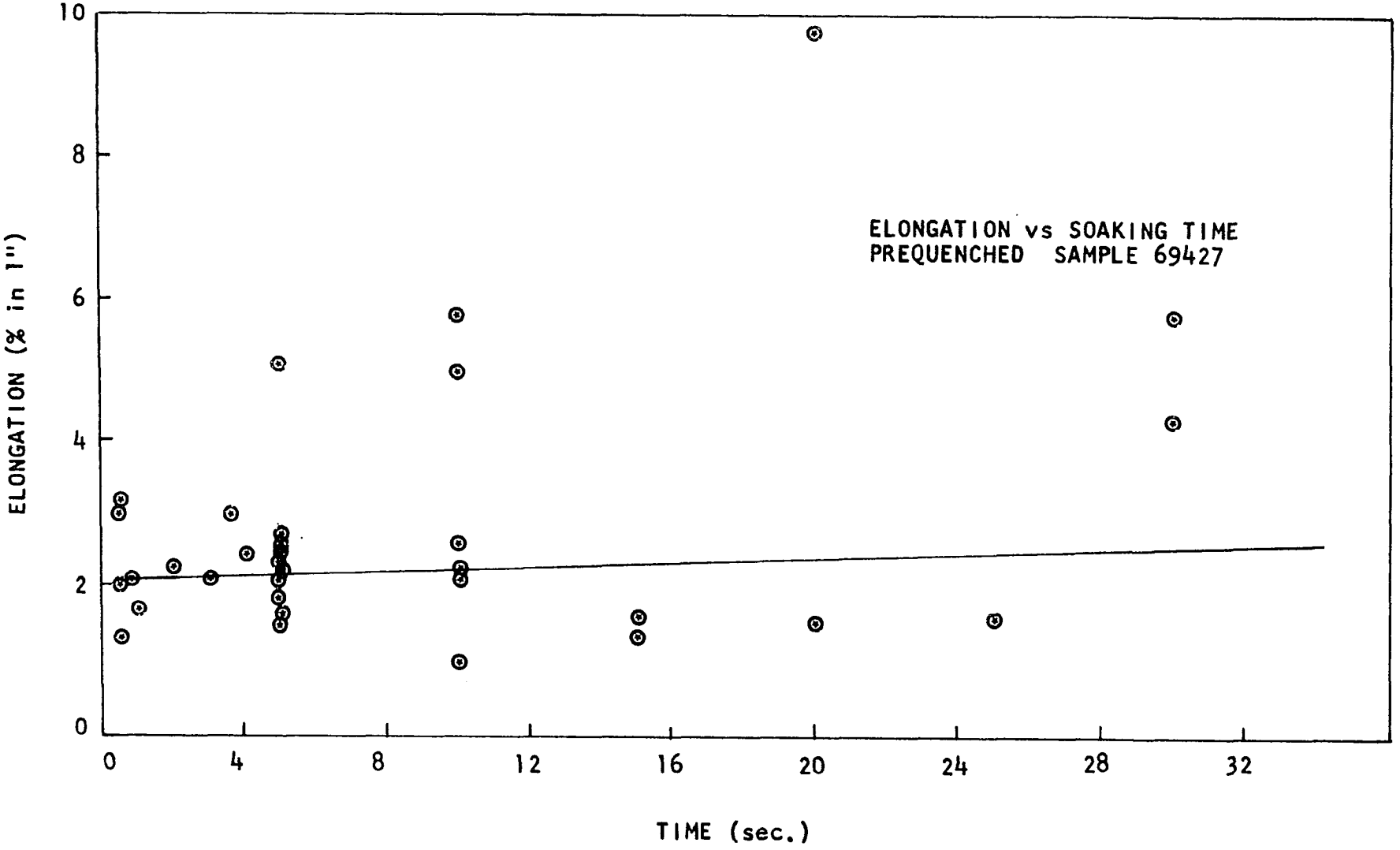


Figure 28

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

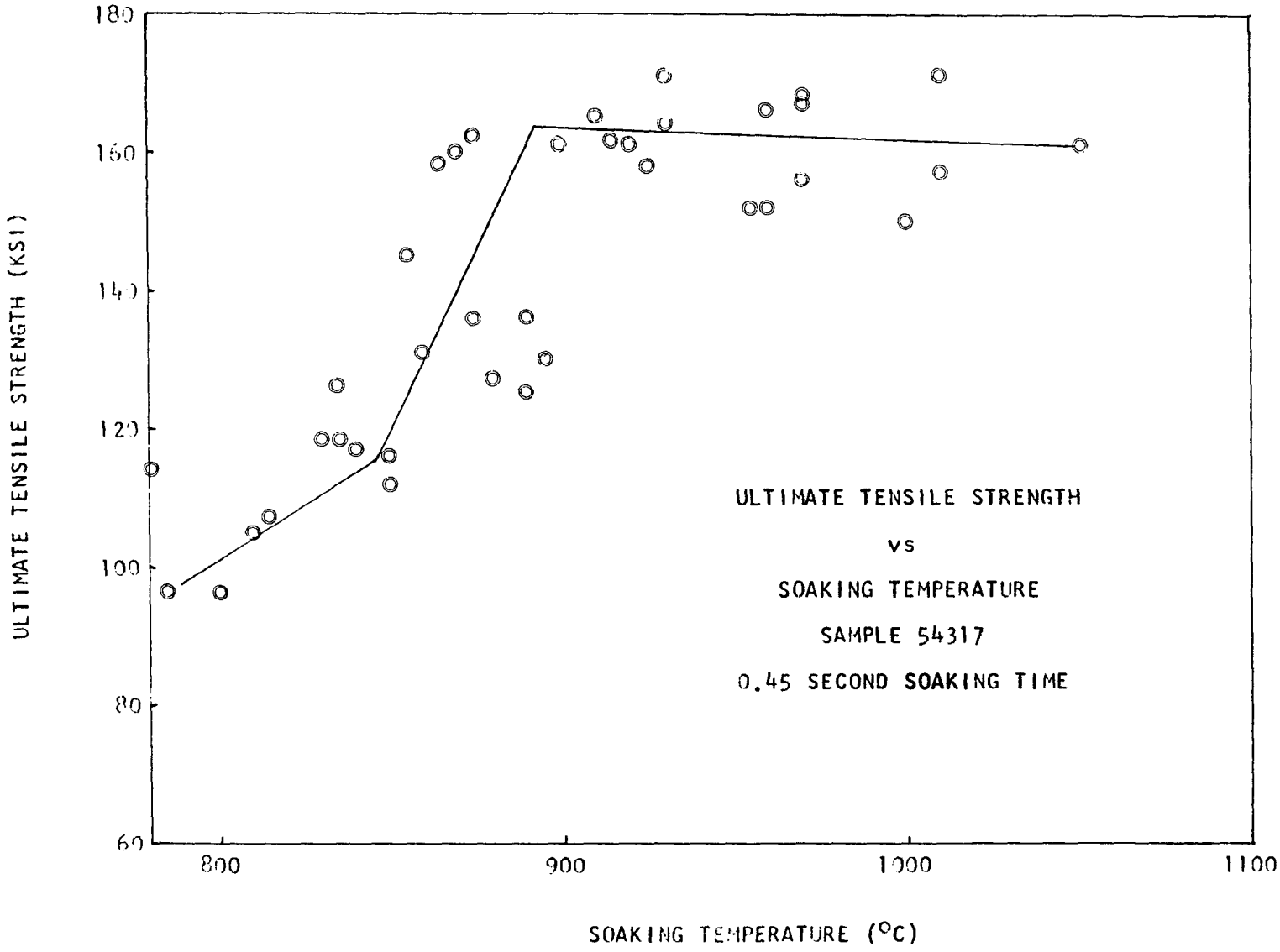


Figure 29

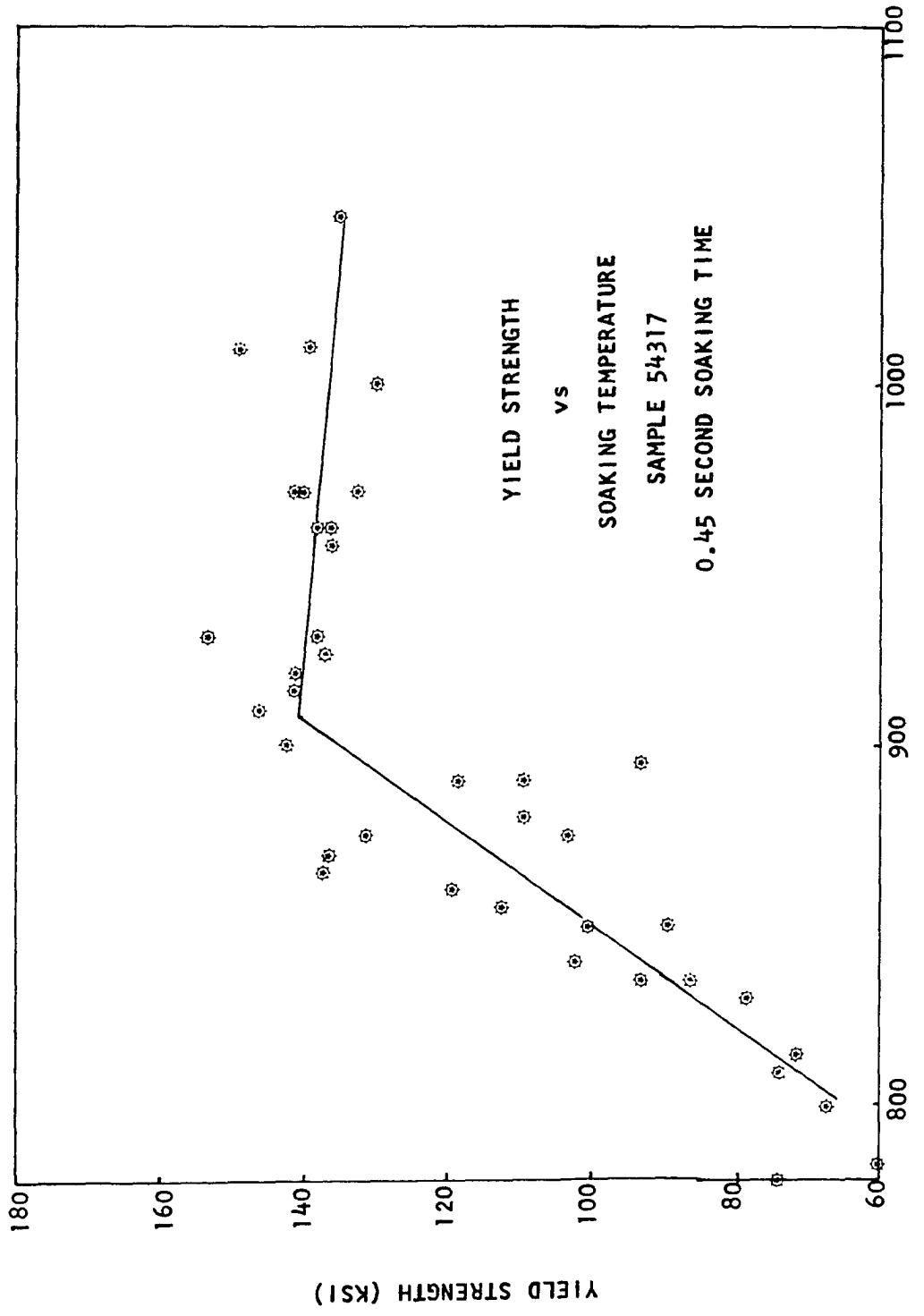


Figure 30

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

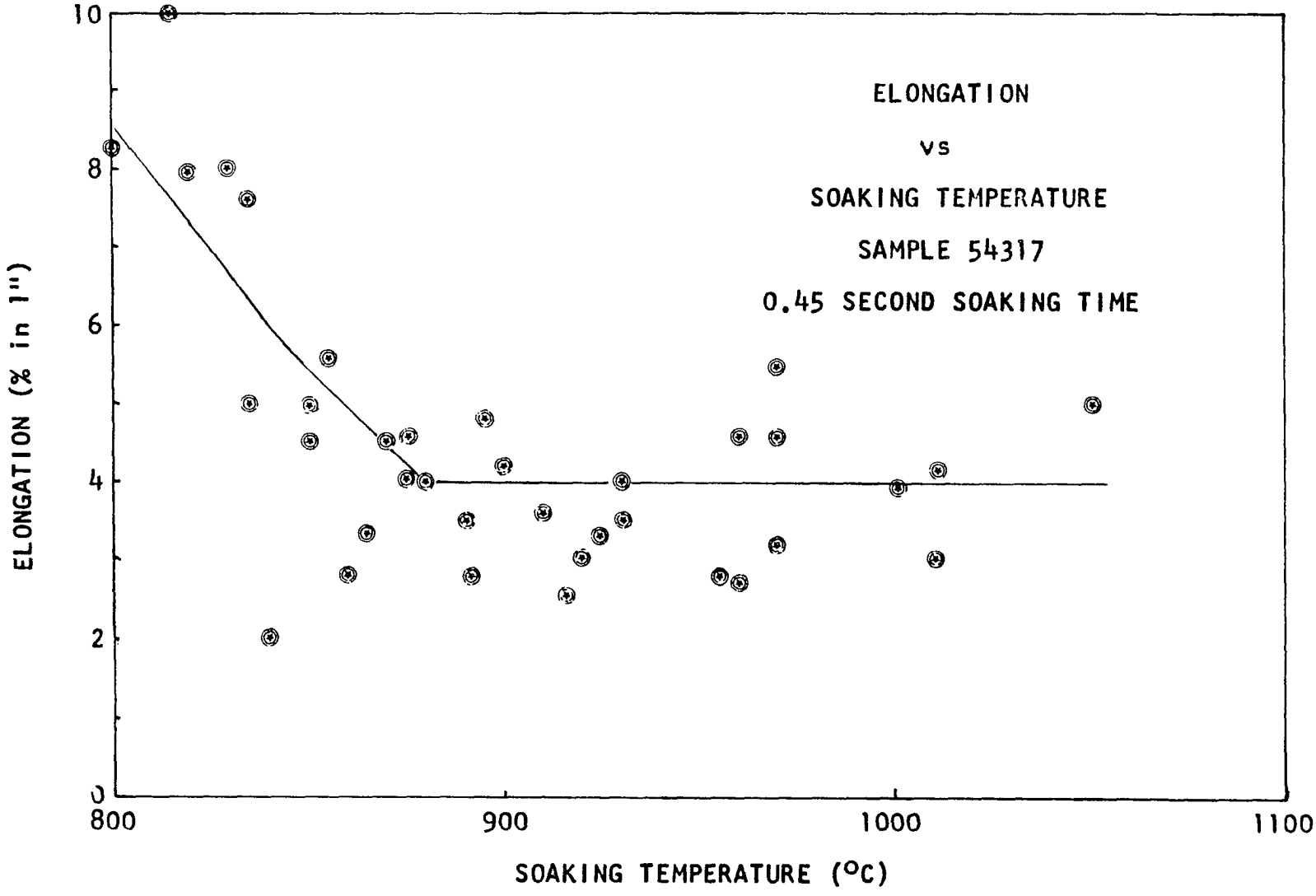


Figure 31

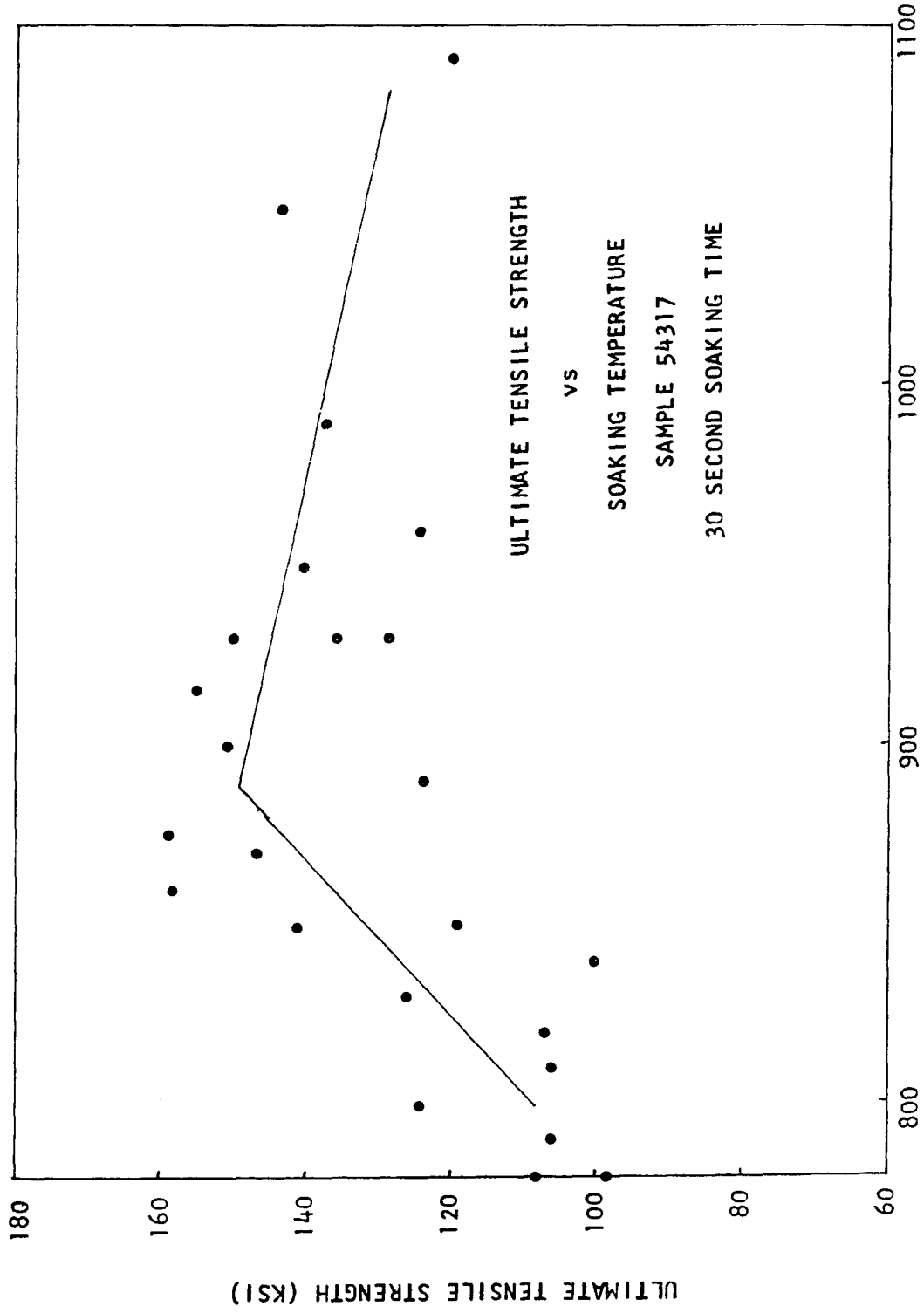


Figure 32

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

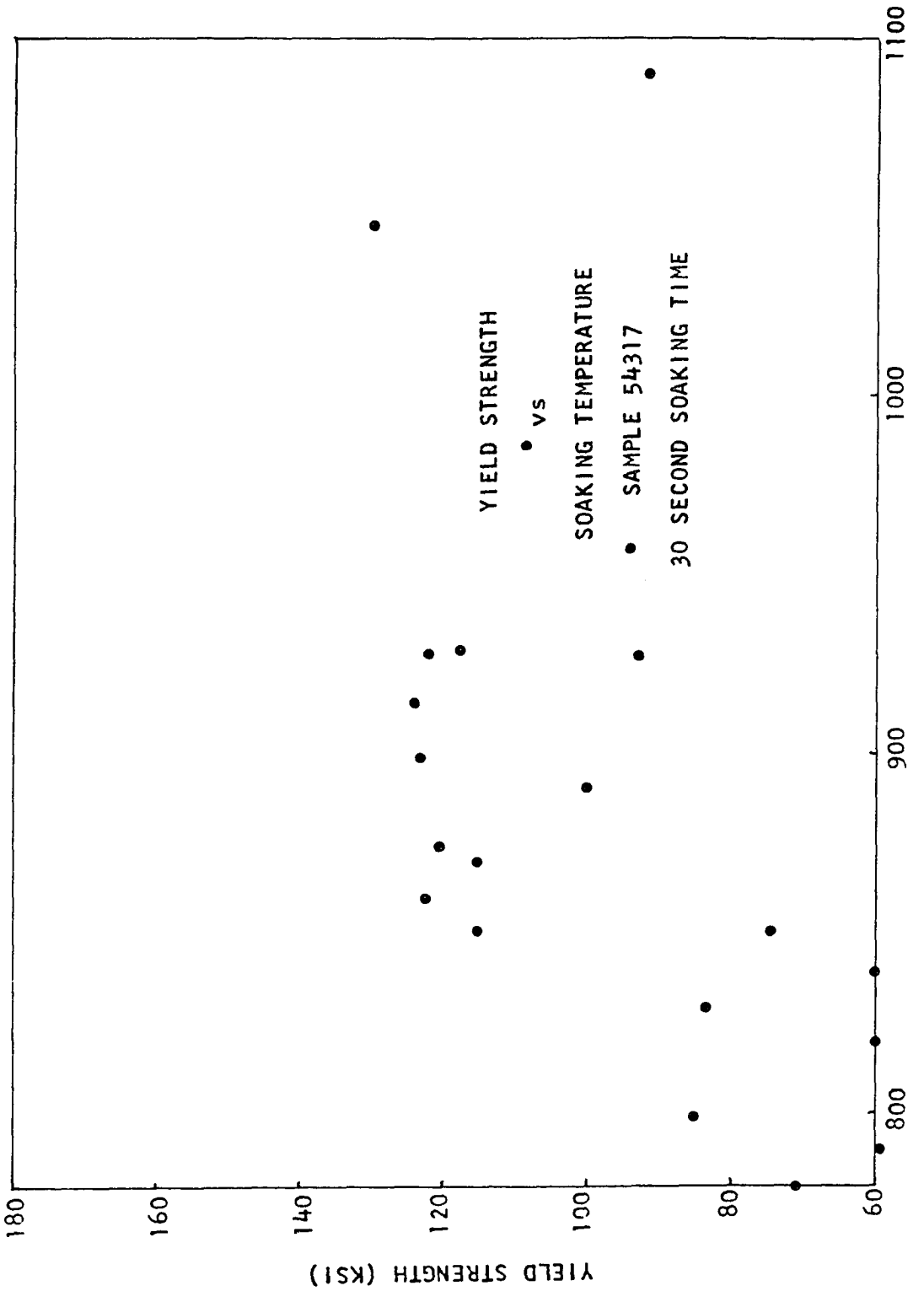


Figure 33

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

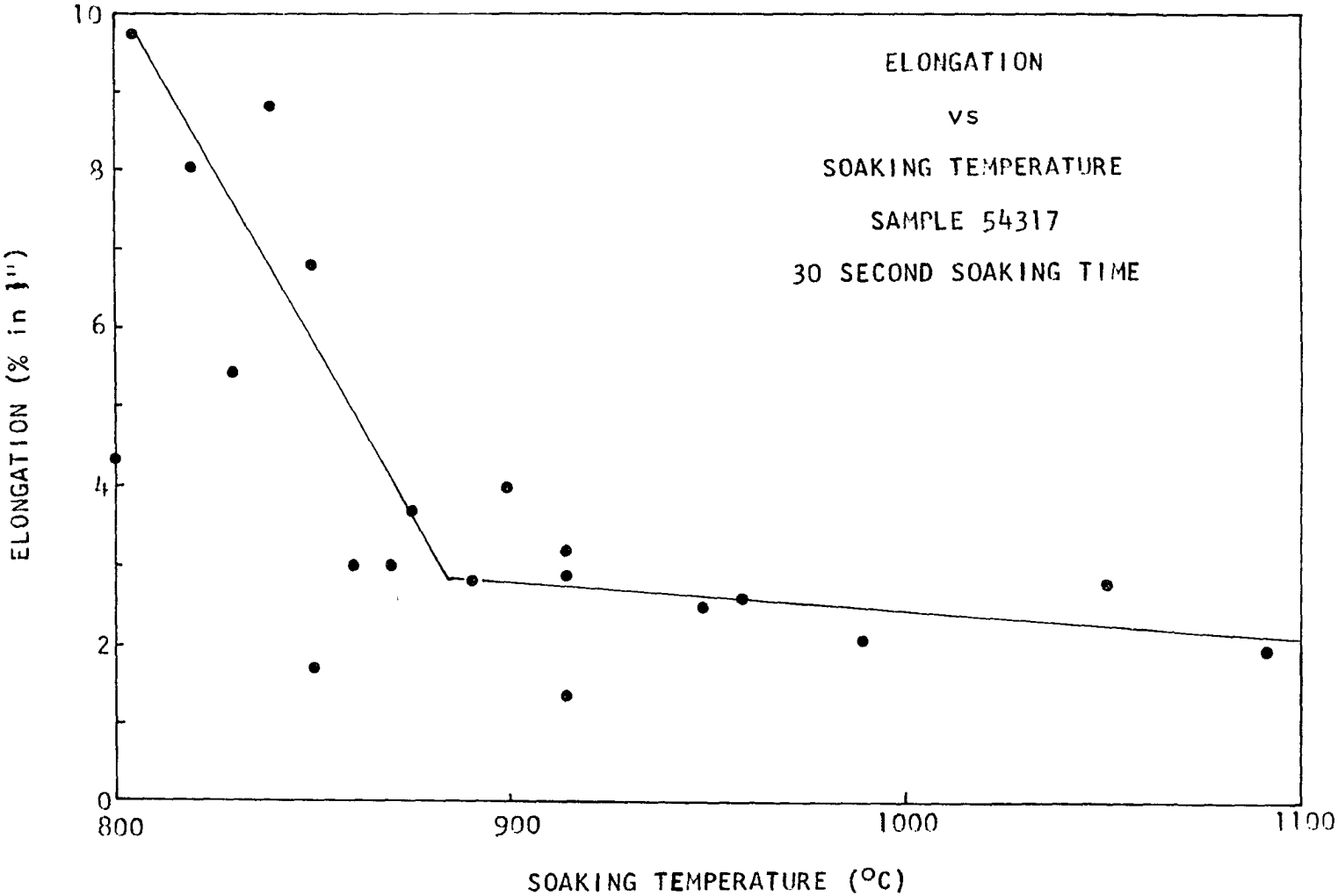


Figure 34

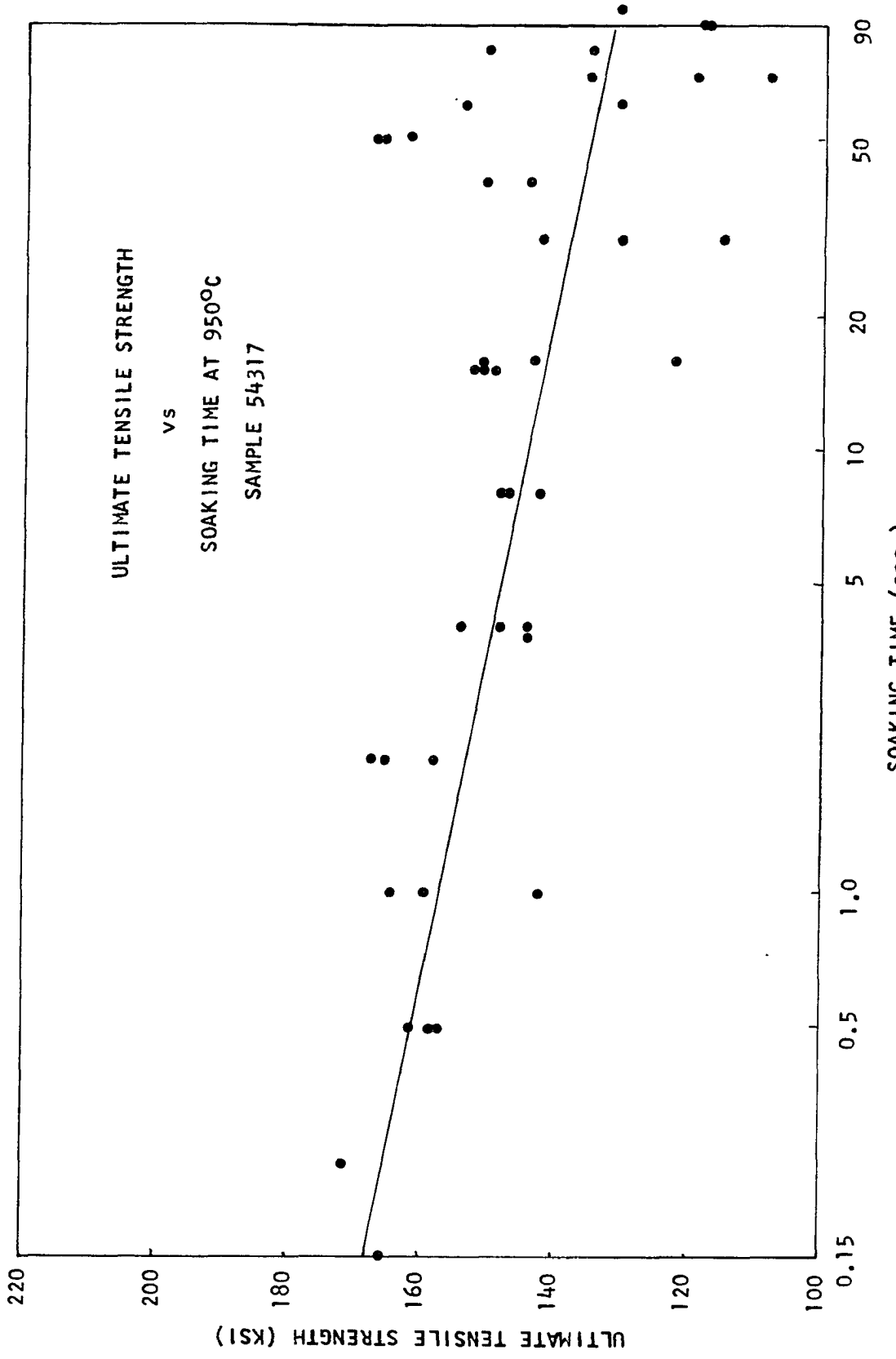


Figure 35

UNIVERSITY OF WINDSOR LIBRARY

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

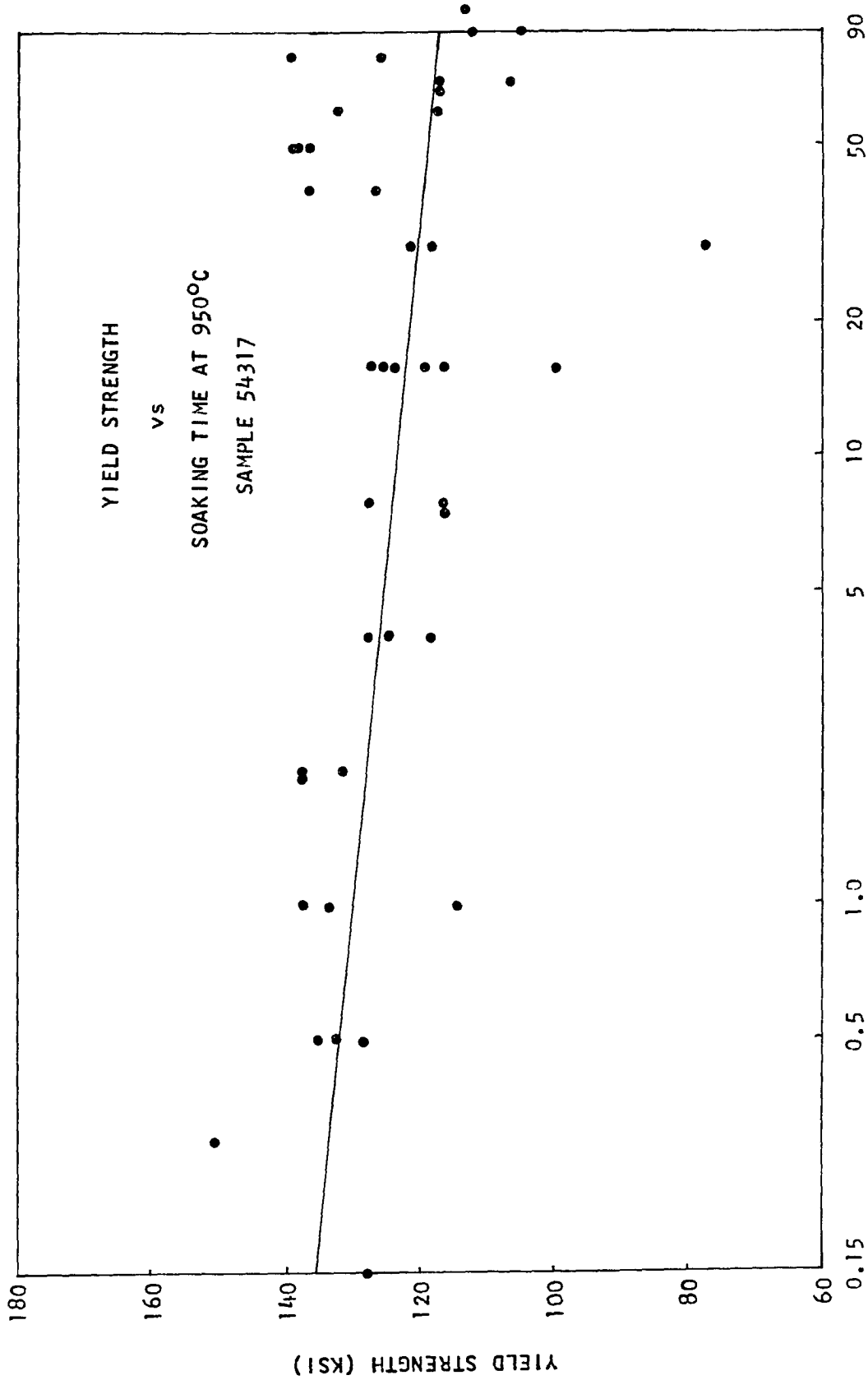


Figure 36

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

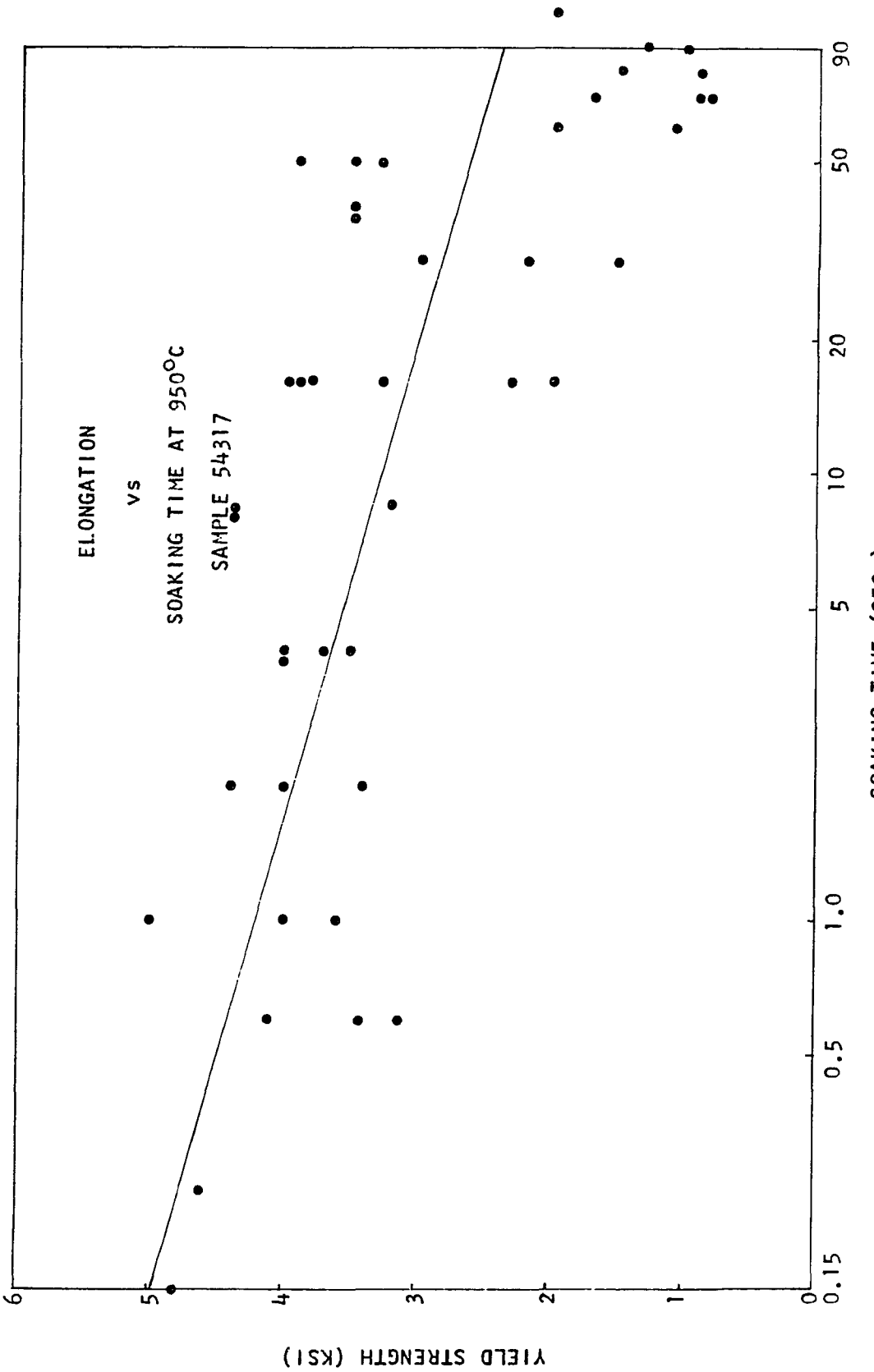


Figure 37

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

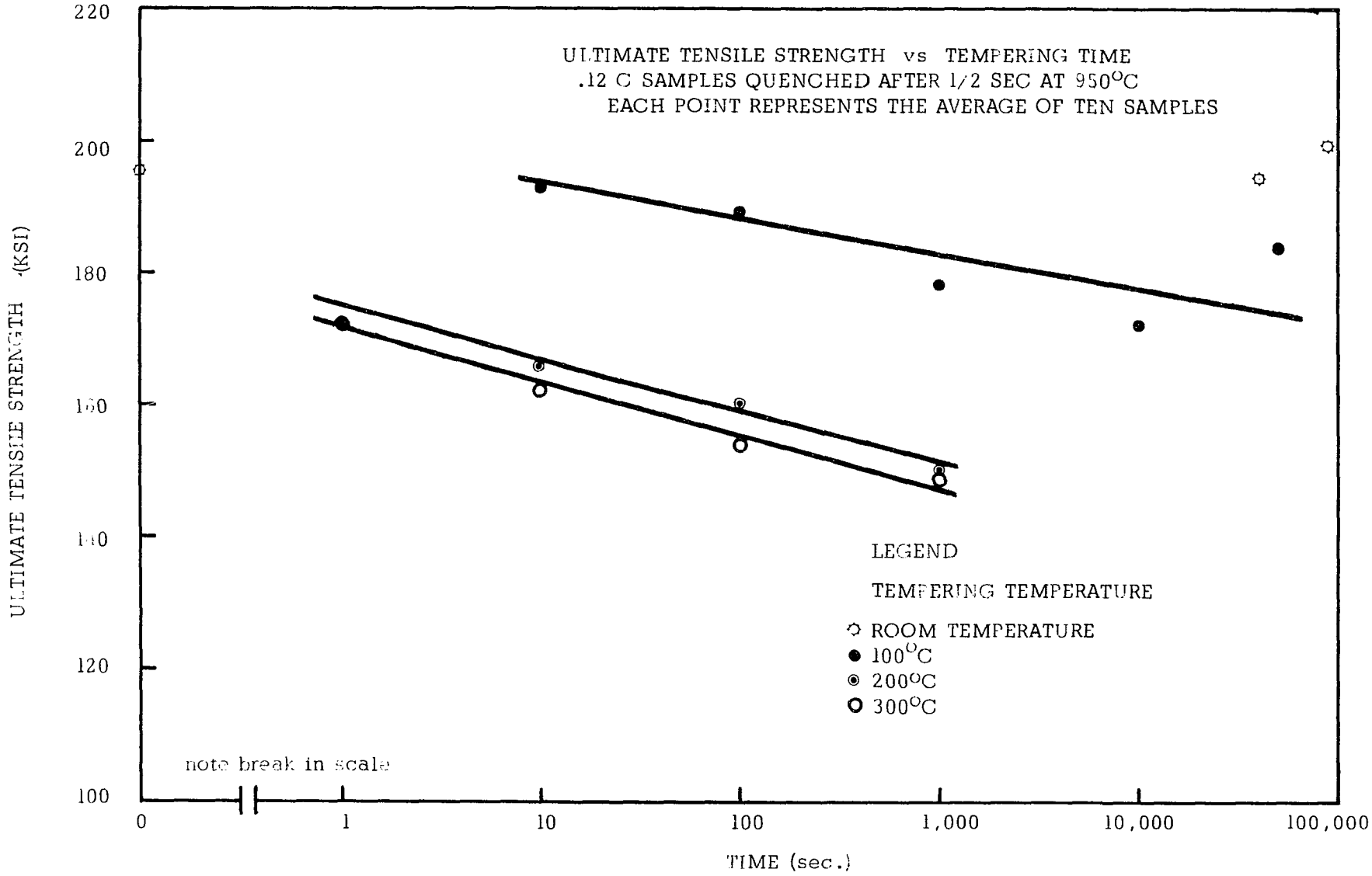


FIGURE 38

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

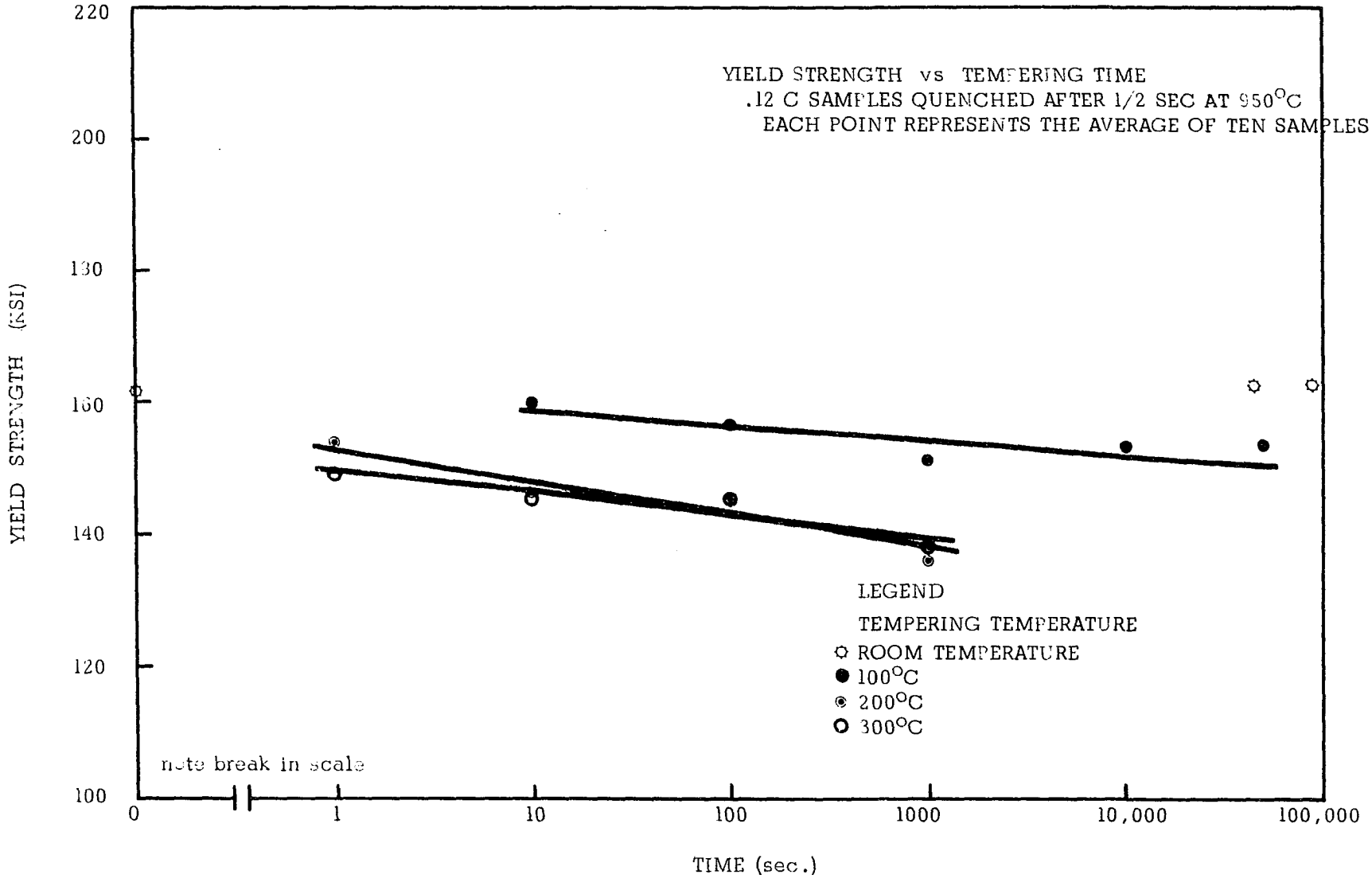


FIGURE 39

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

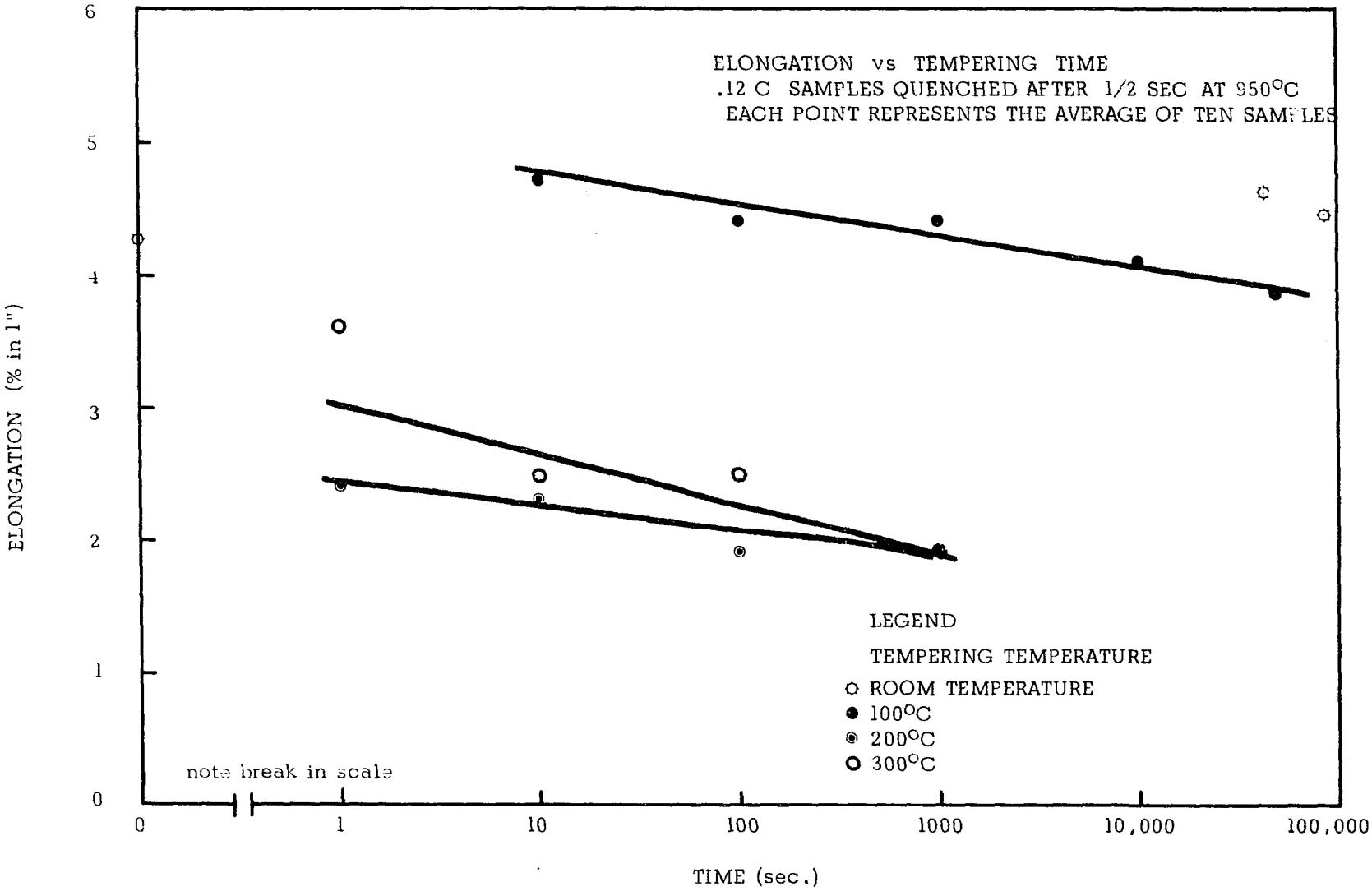


FIGURE 40

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

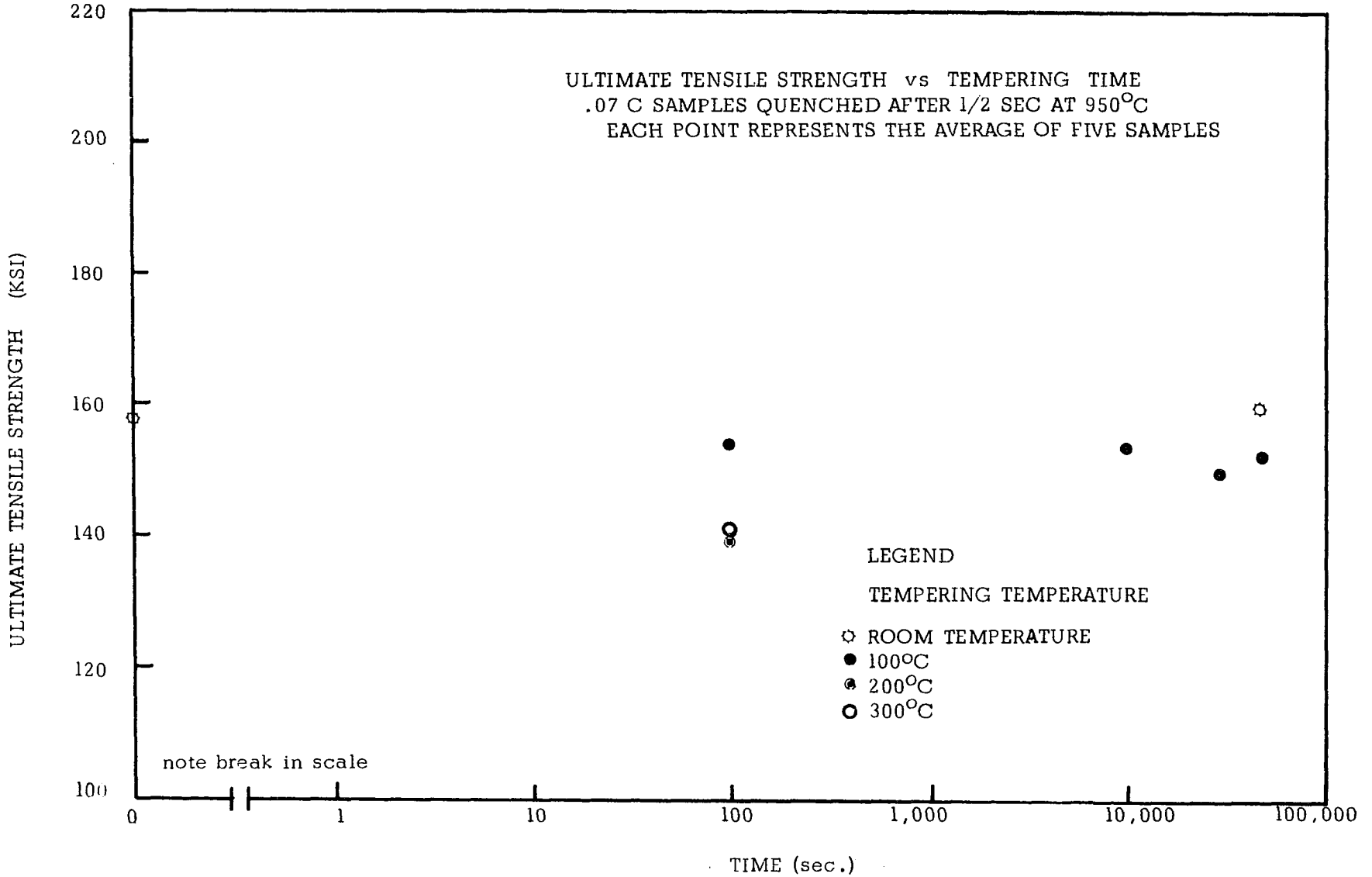


FIGURE 41

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

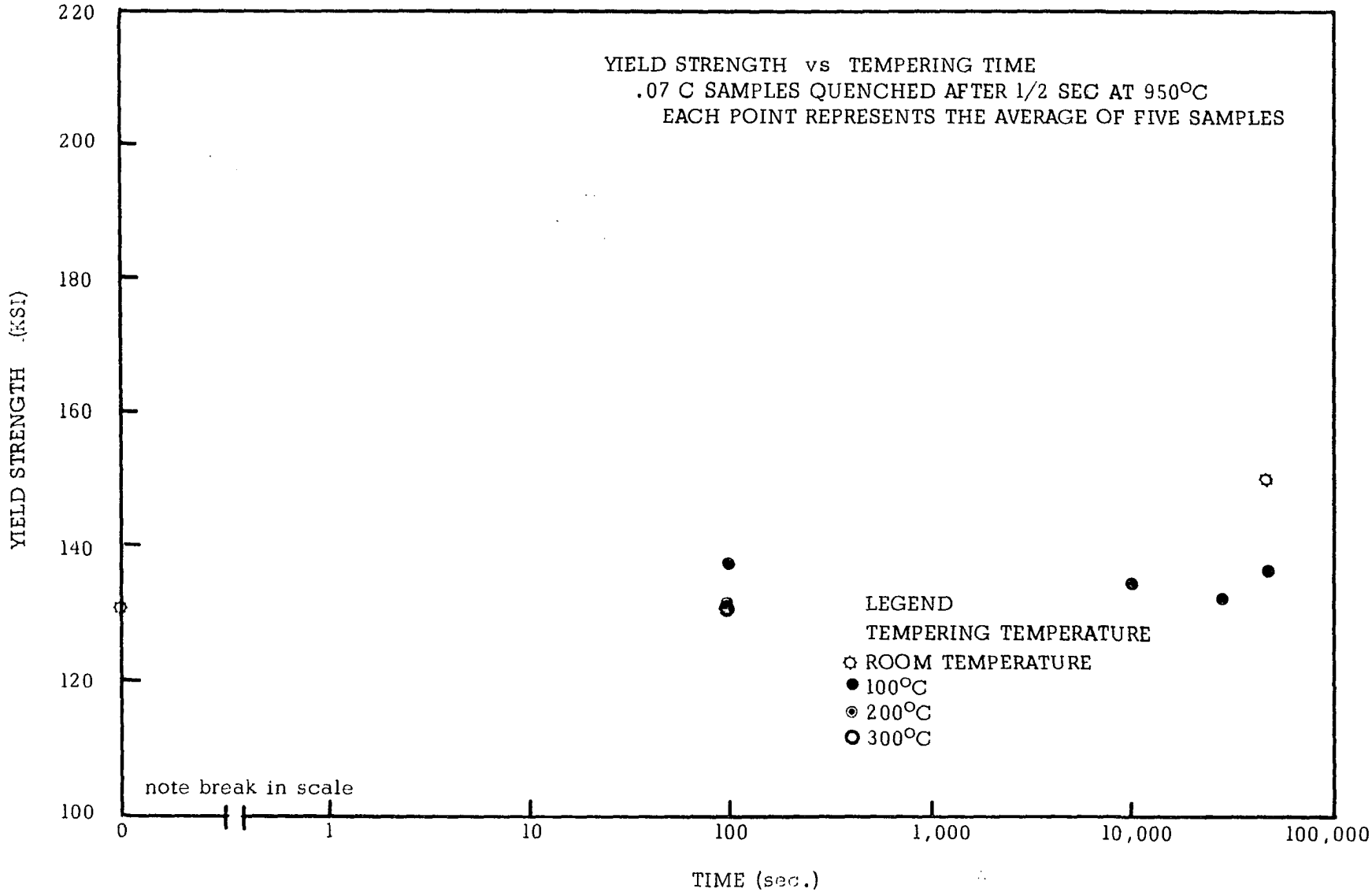


FIGURE 42

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

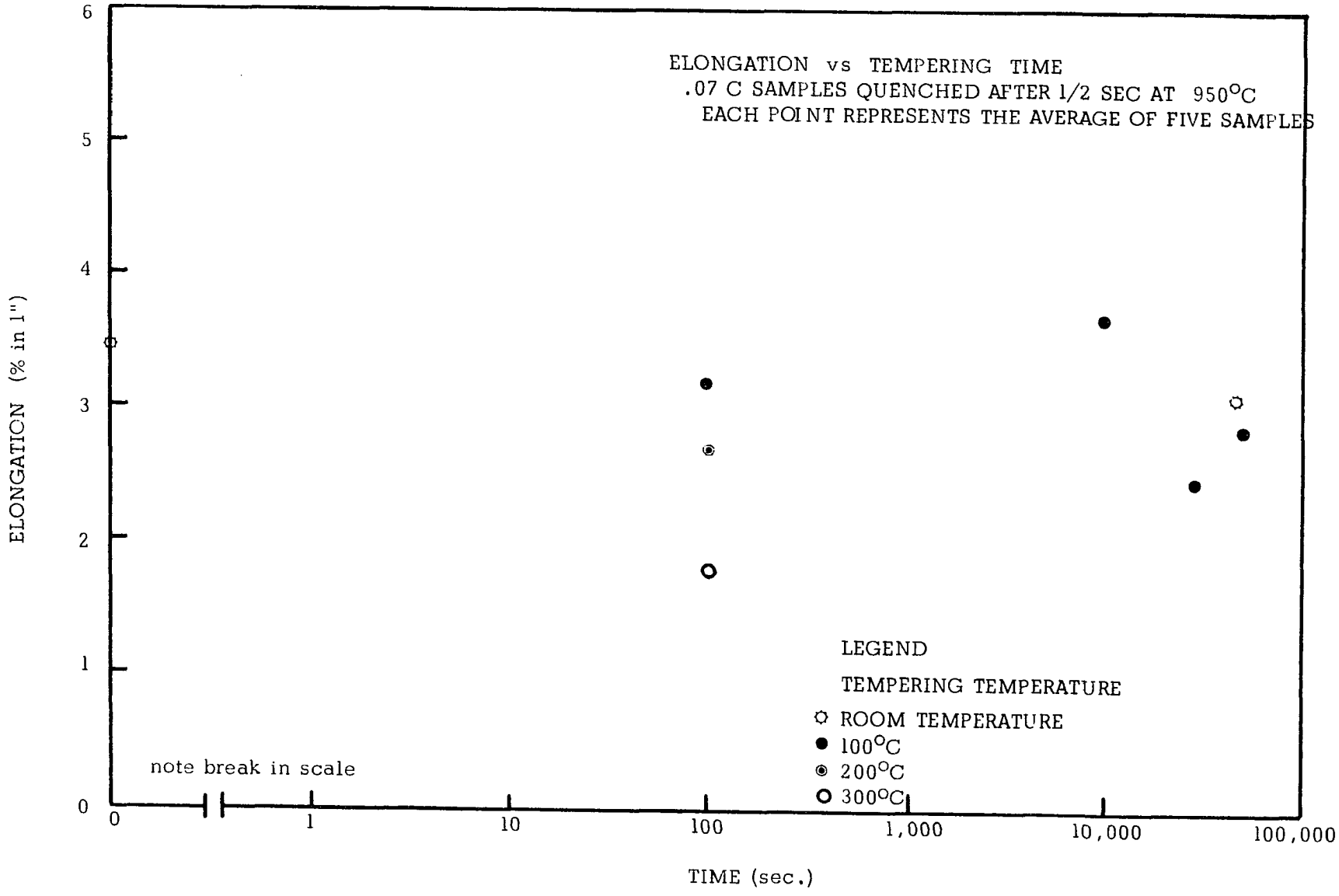


FIGURE 43

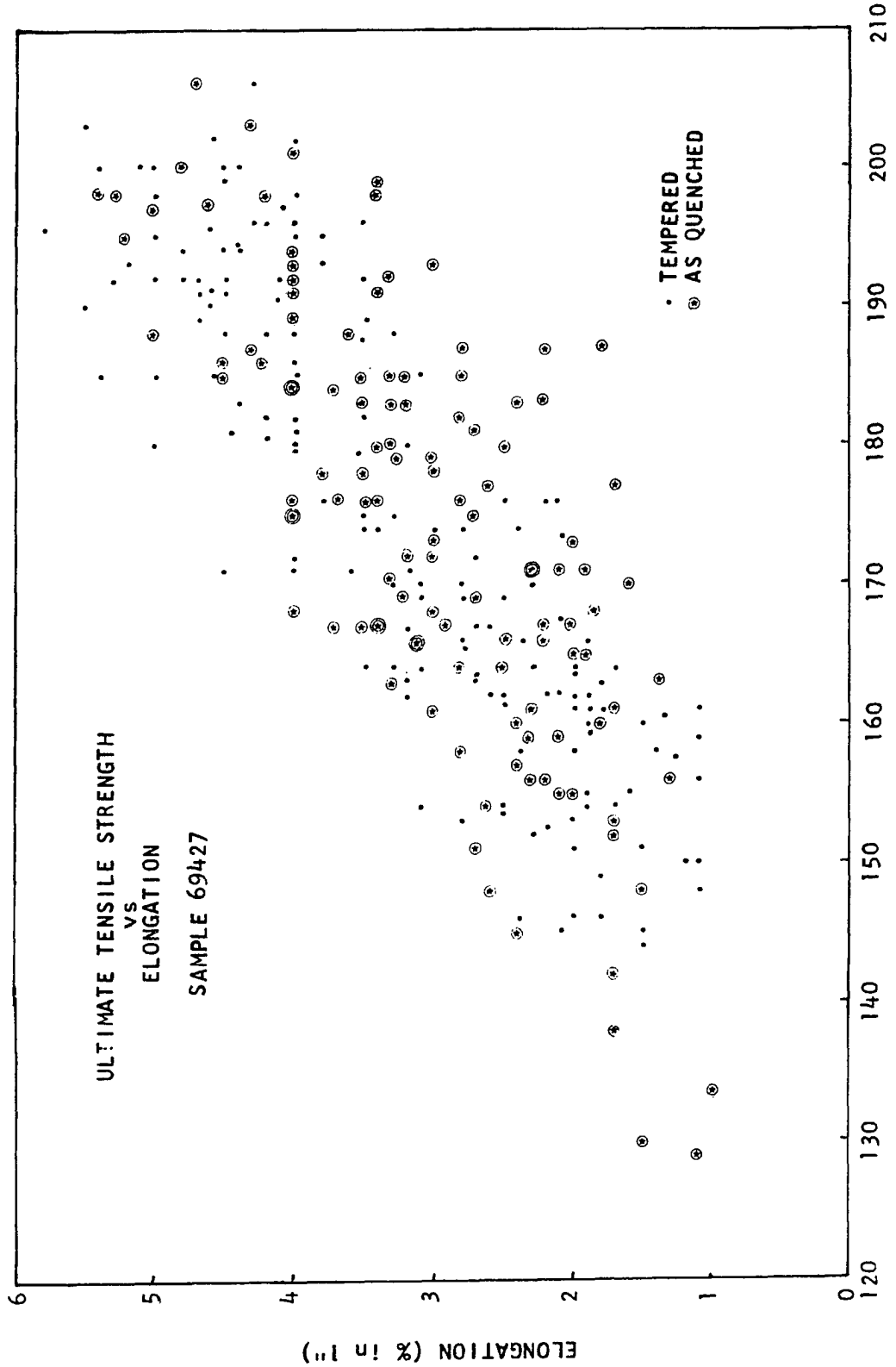


Figure 44

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

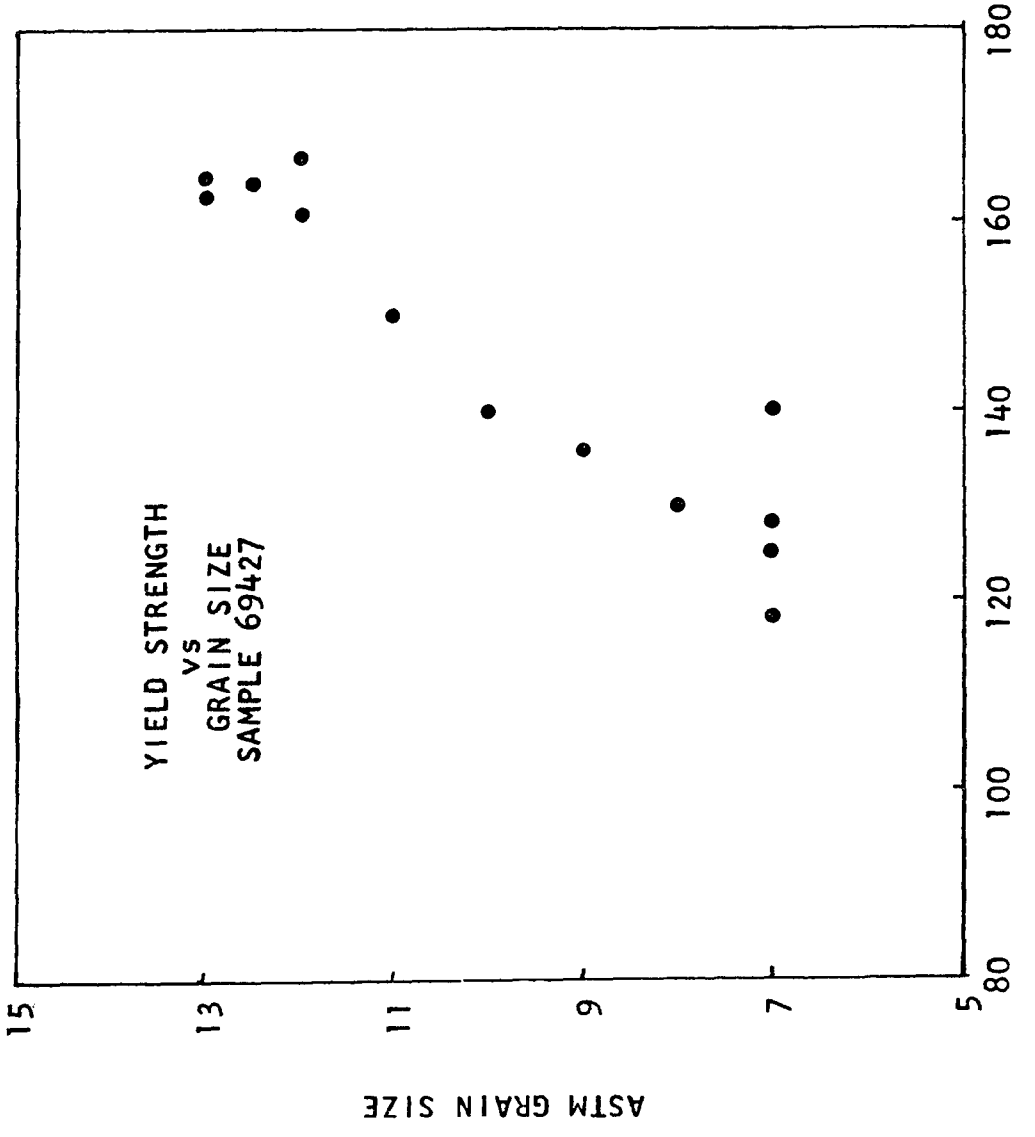


Figure 45

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

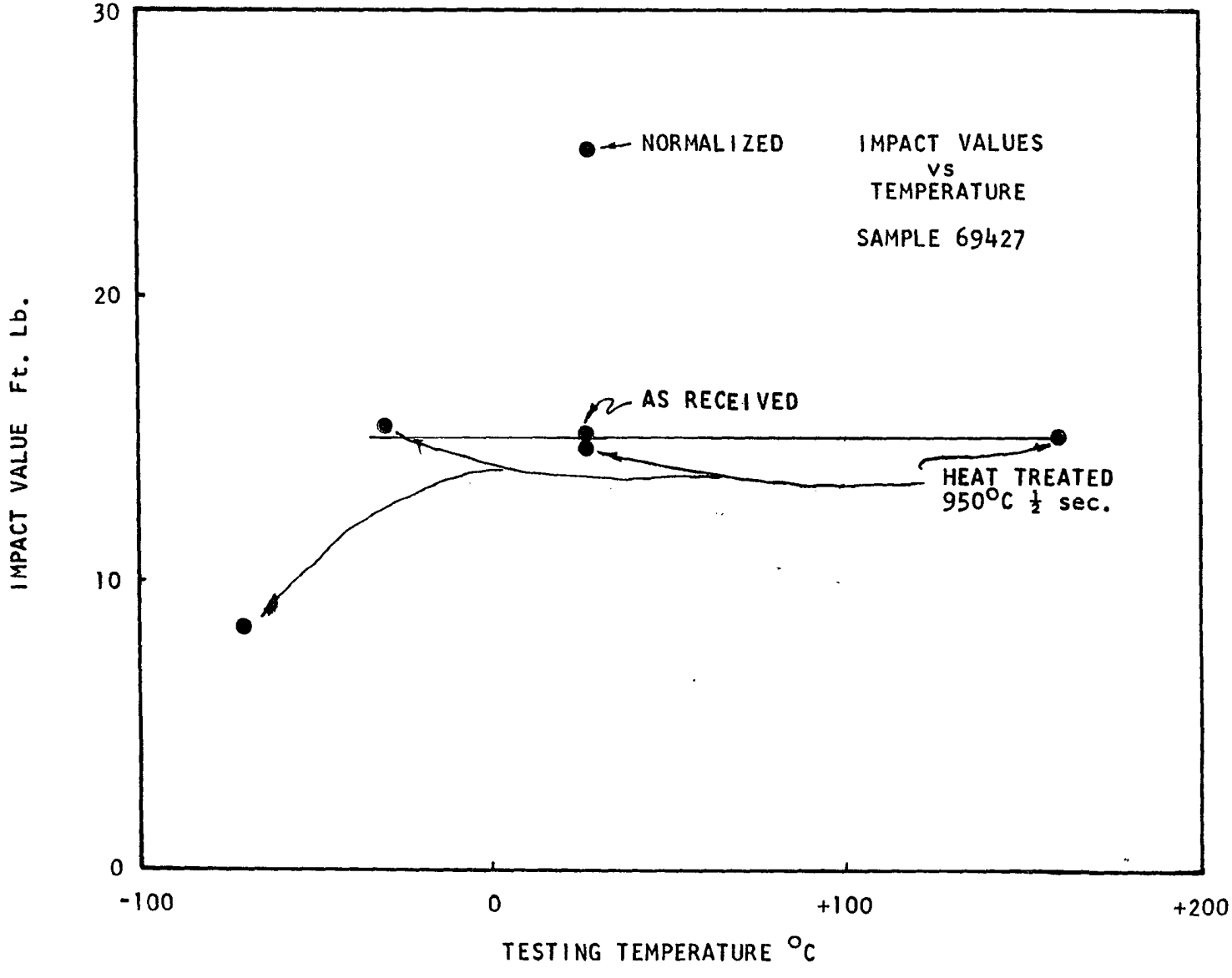


Figure 46

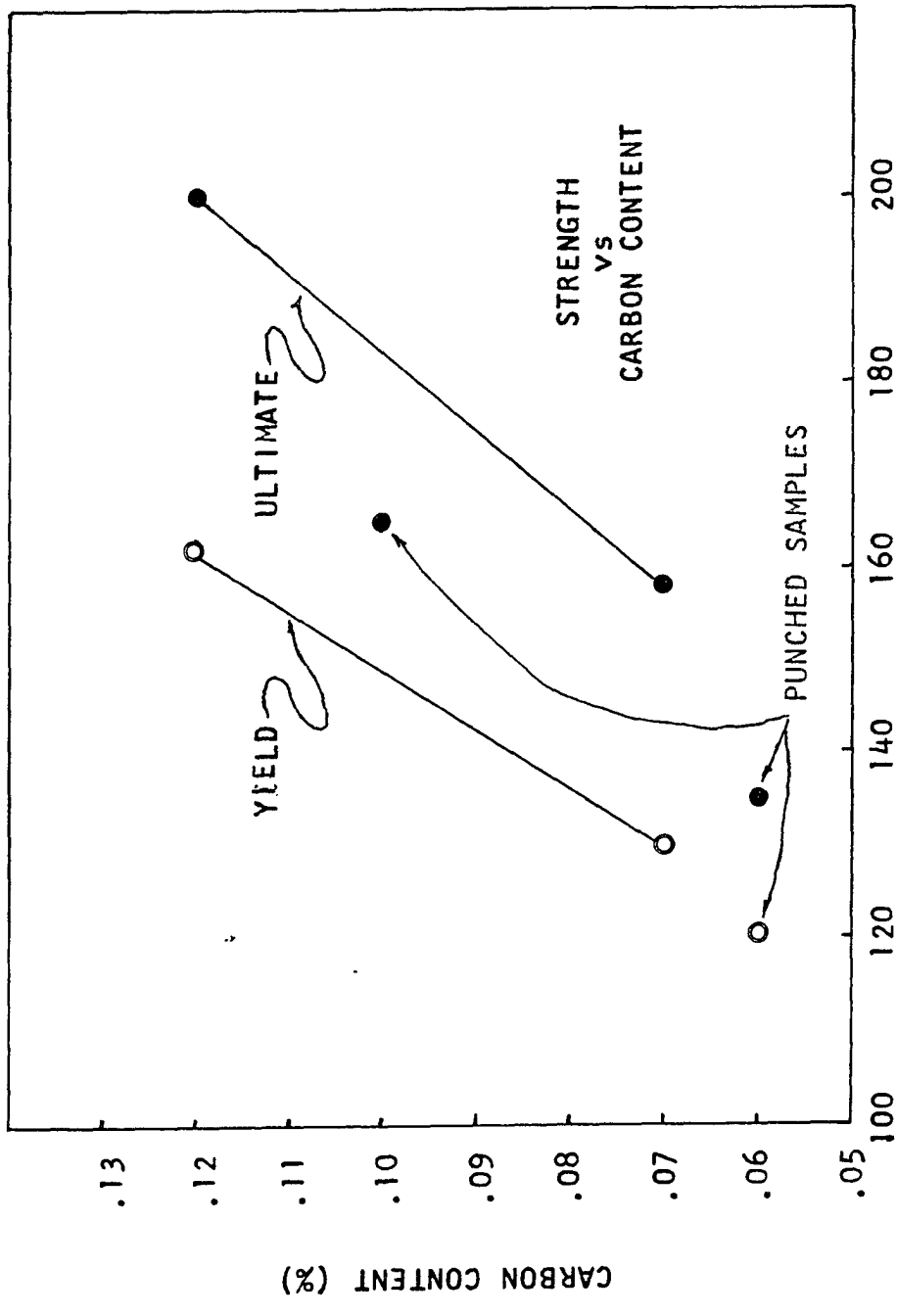


Figure 47

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

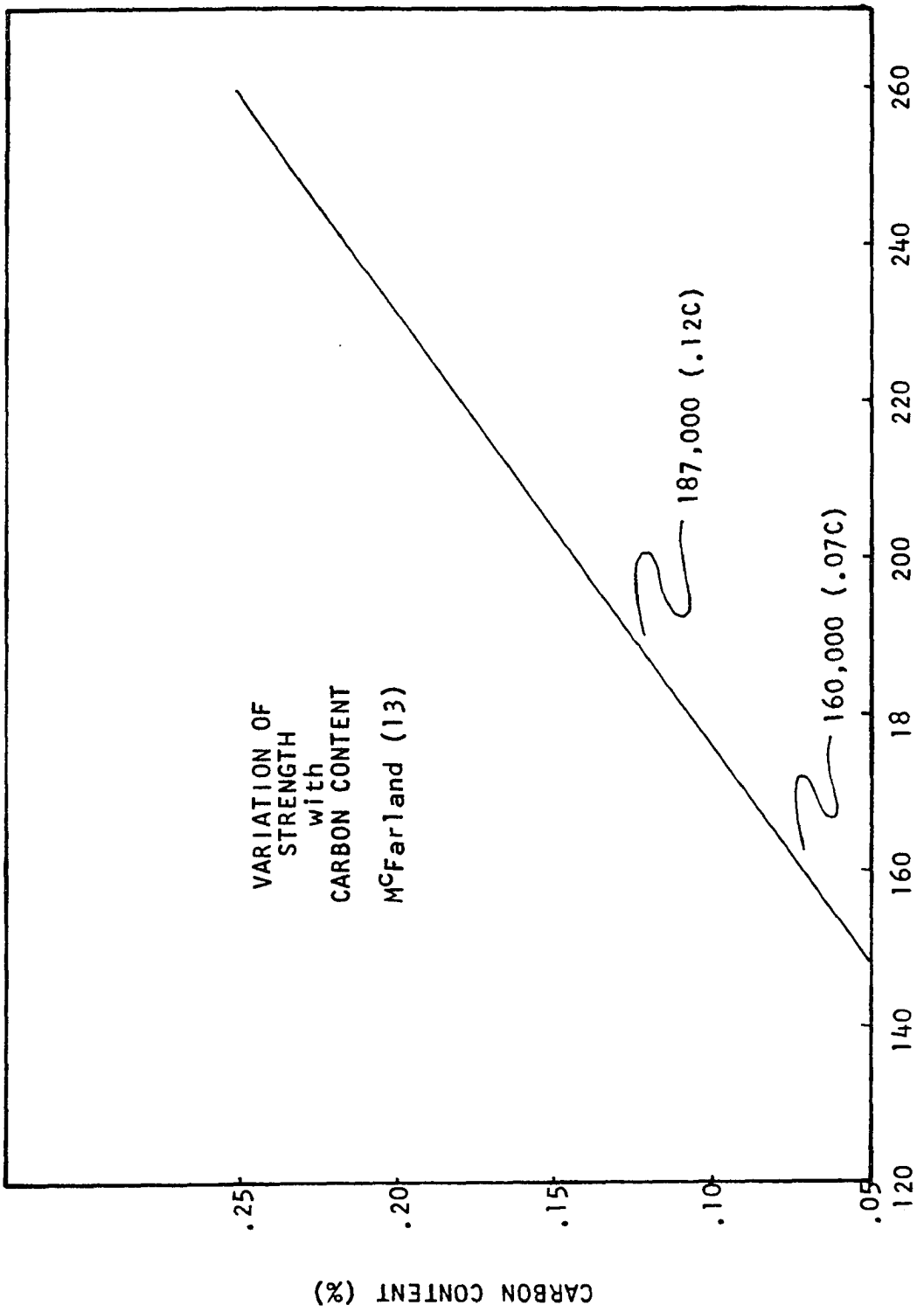


Figure 48

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

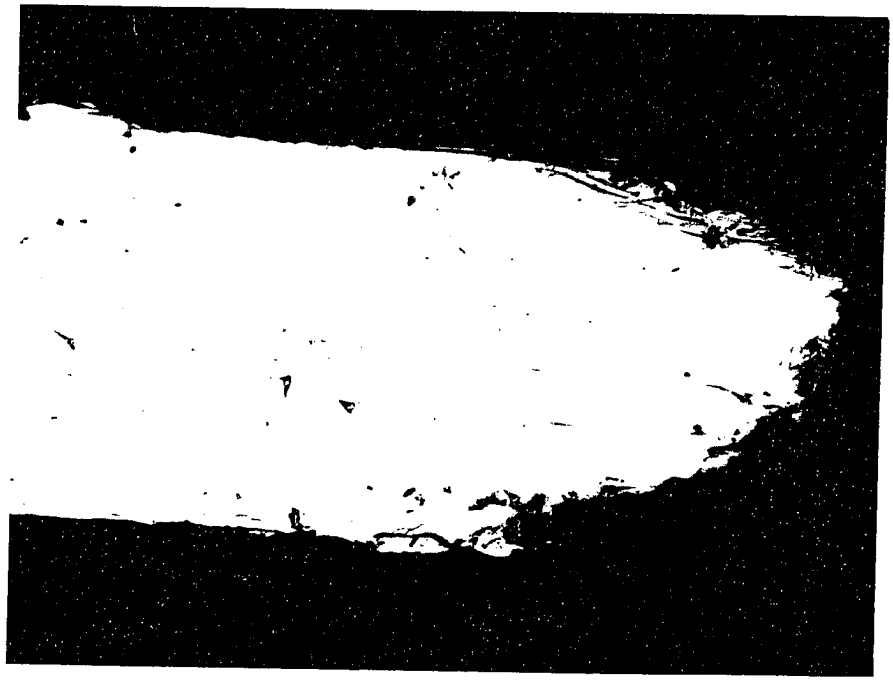


Figure 49 IMPACT SAMPLE CROSS SECTION OF ONE LAMINA
150°C

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

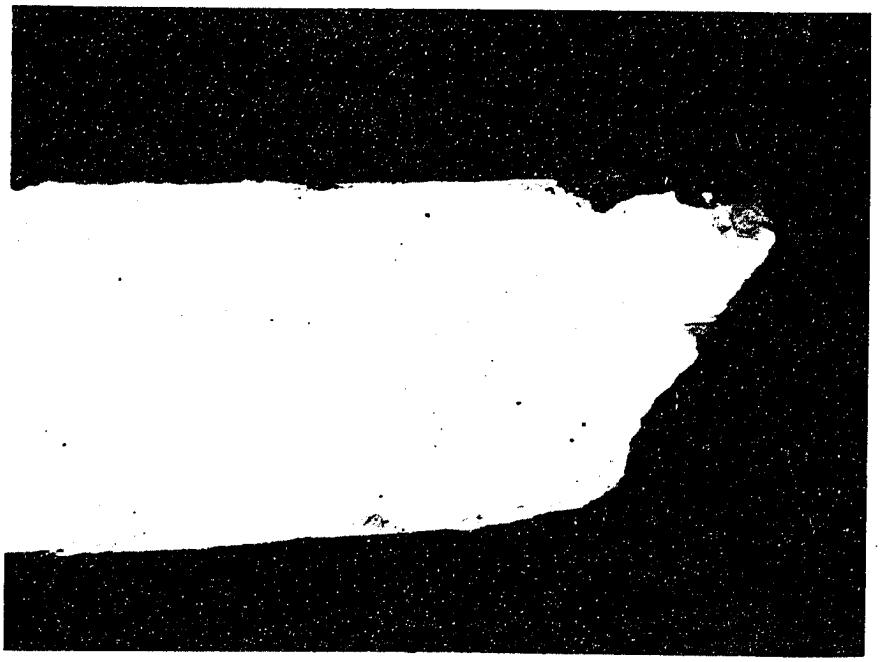


Figure 50 IMPACT SAMPLE CROSS SECTION OF ONE LAMINA
27°C

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 51 SPECIMEN GIVEN SHORT SOAKING TIME
0.12C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

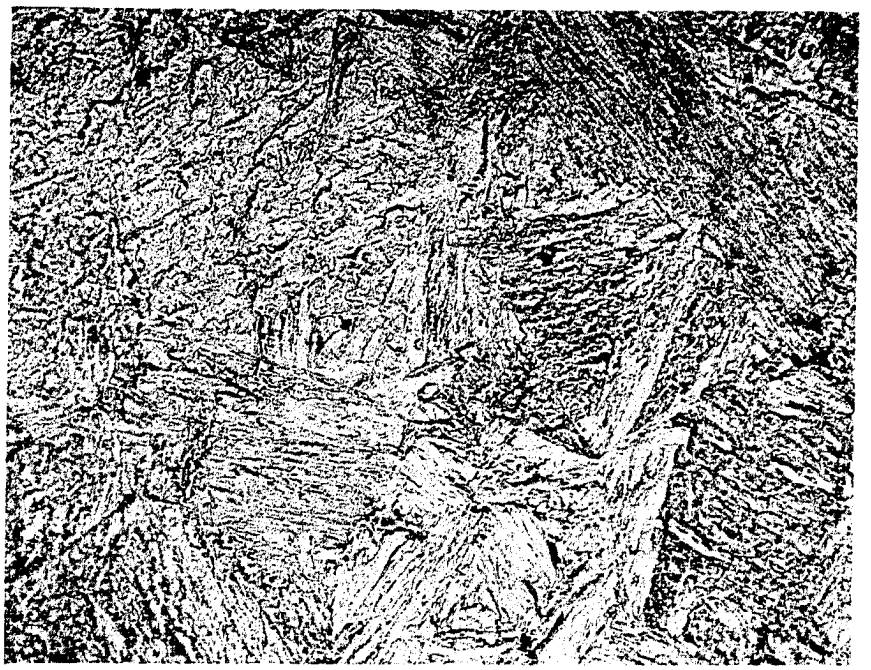


Figure 52 SPECIMEN GIVEN LONG SOAKING TIME
0.12C x 1400
(SEE ALSO FIGURE 57)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

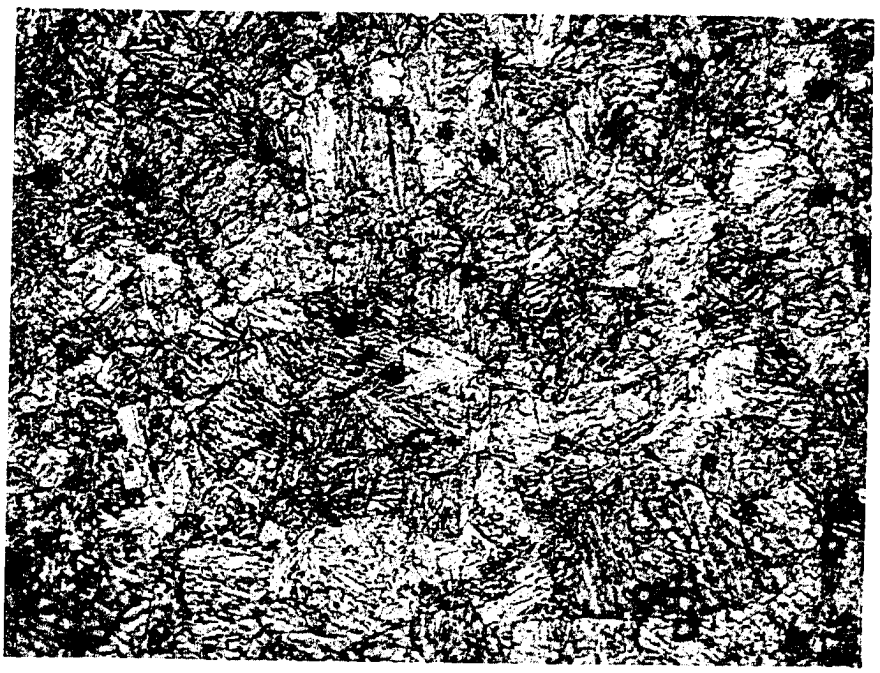


Figure 53 SPECIMEN TEMPERED AT 300°C FOR 1 MIN.
0.12C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

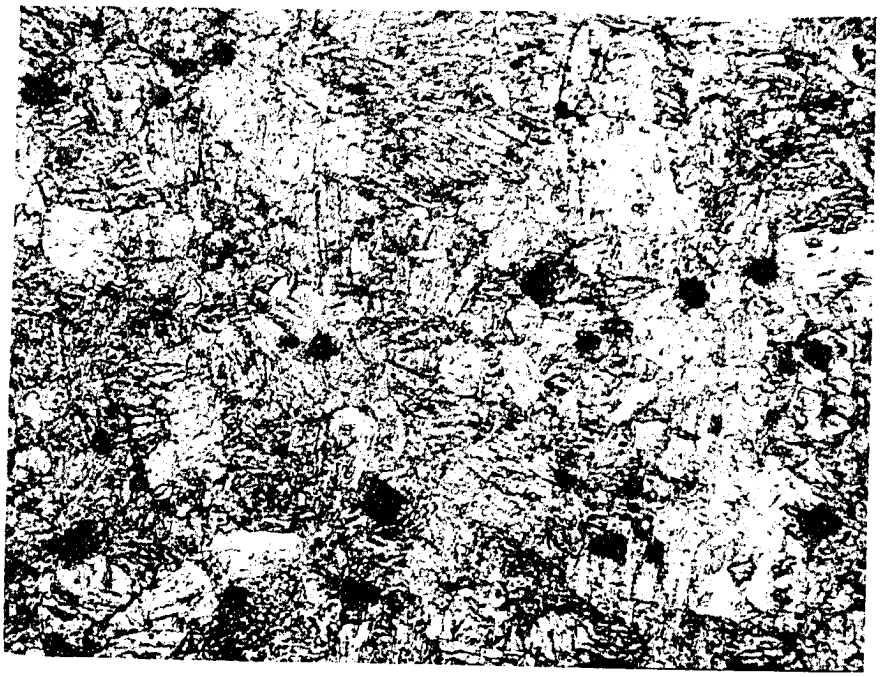


Figure 54 SPECIMEN TEMPERED AT 300°C FOR 10 MIN.
0.12C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

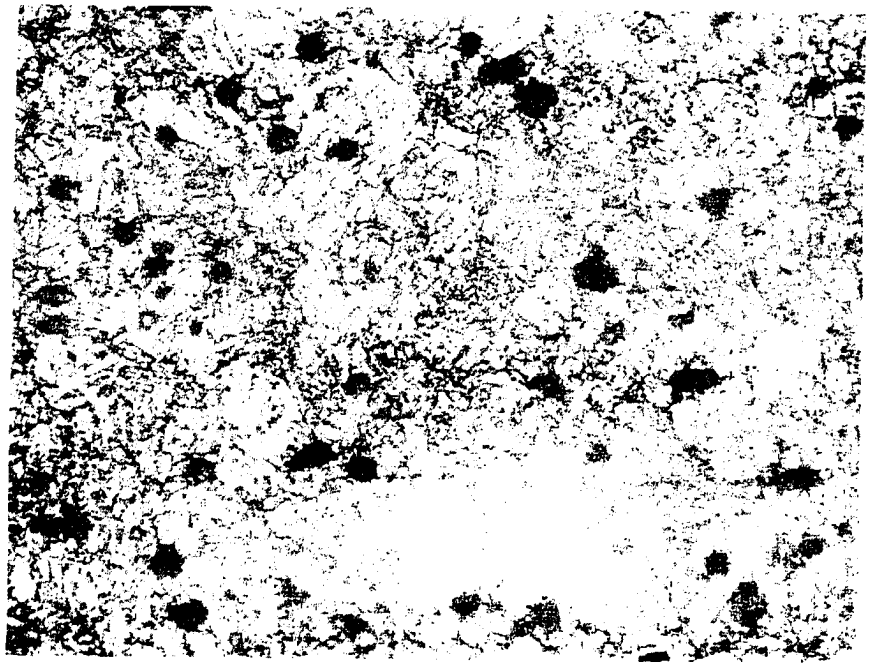


Figure 55 SPECIMEN TEMPERED AT 300°C FOR 100 MIN.
0.12C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

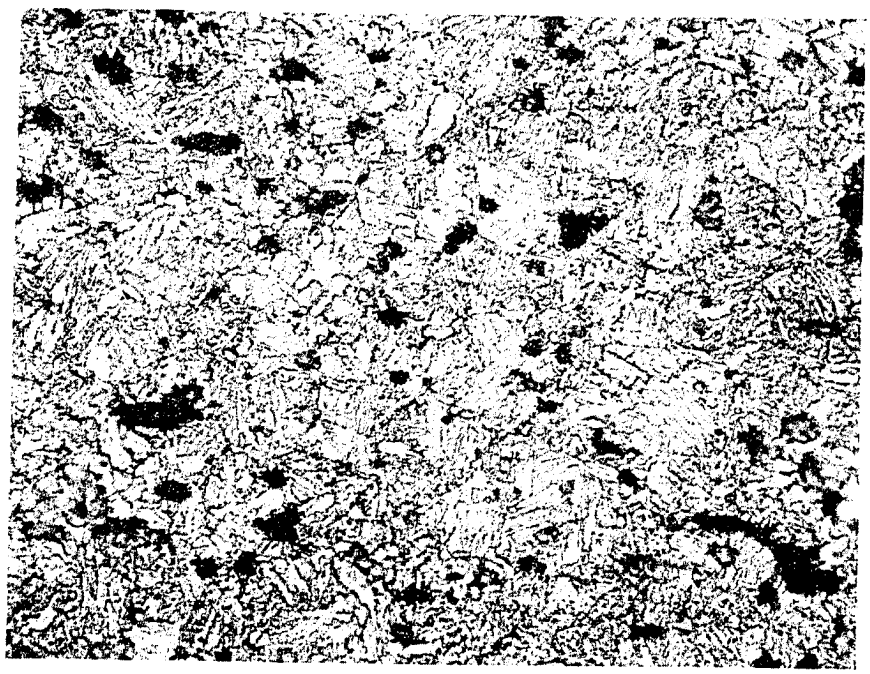


Figure 56 SPECIMEN TEMPERED AT 100°C FOR 10,000 MIN.
0.07C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

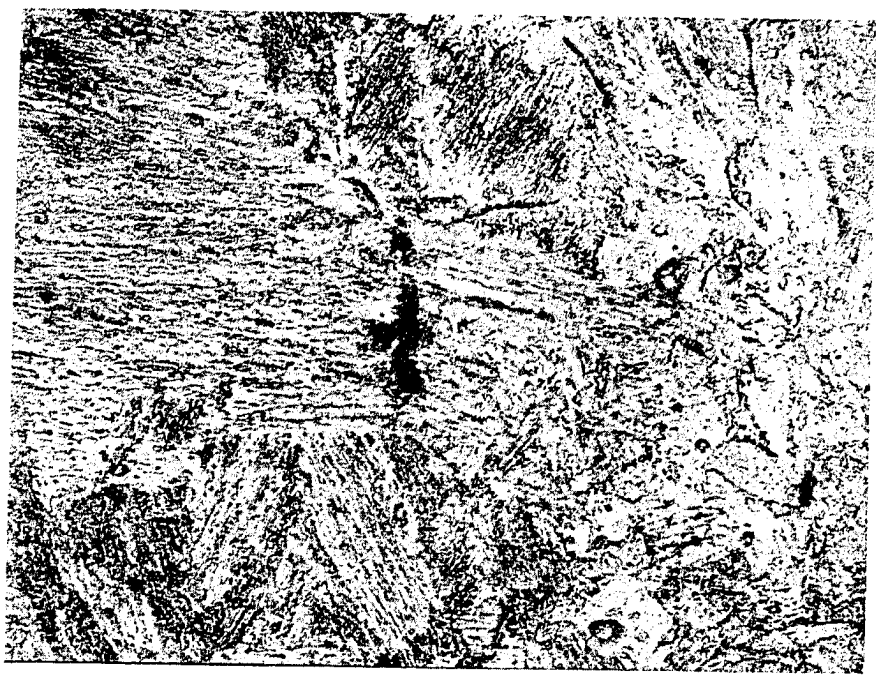


Figure 57 SPECIMEN GIVEN LONG SOAKING TIME SHOW HUGE GRAINS THAT CAN DEVELOP
0.12C x 1400

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

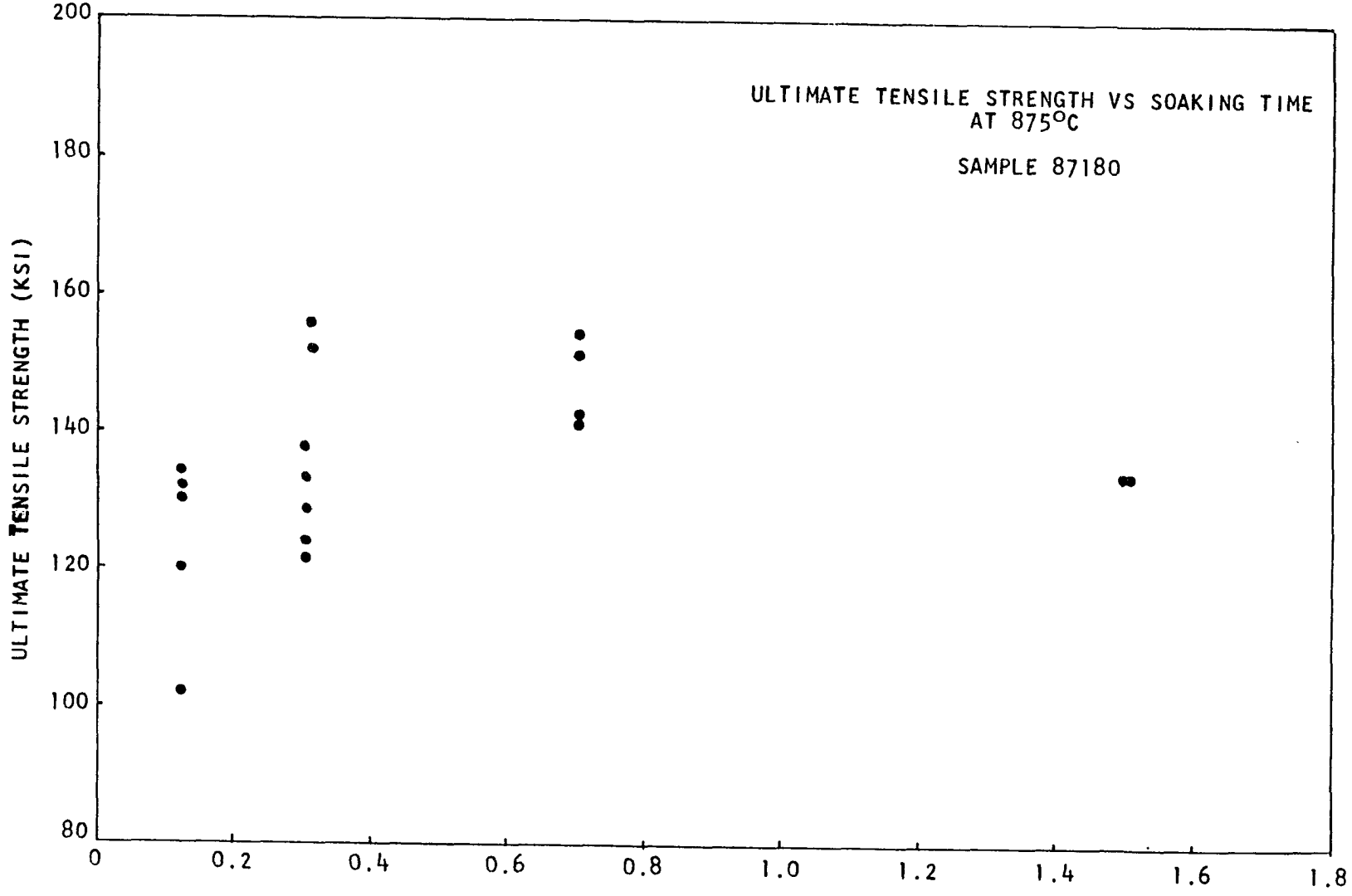


Figure 58

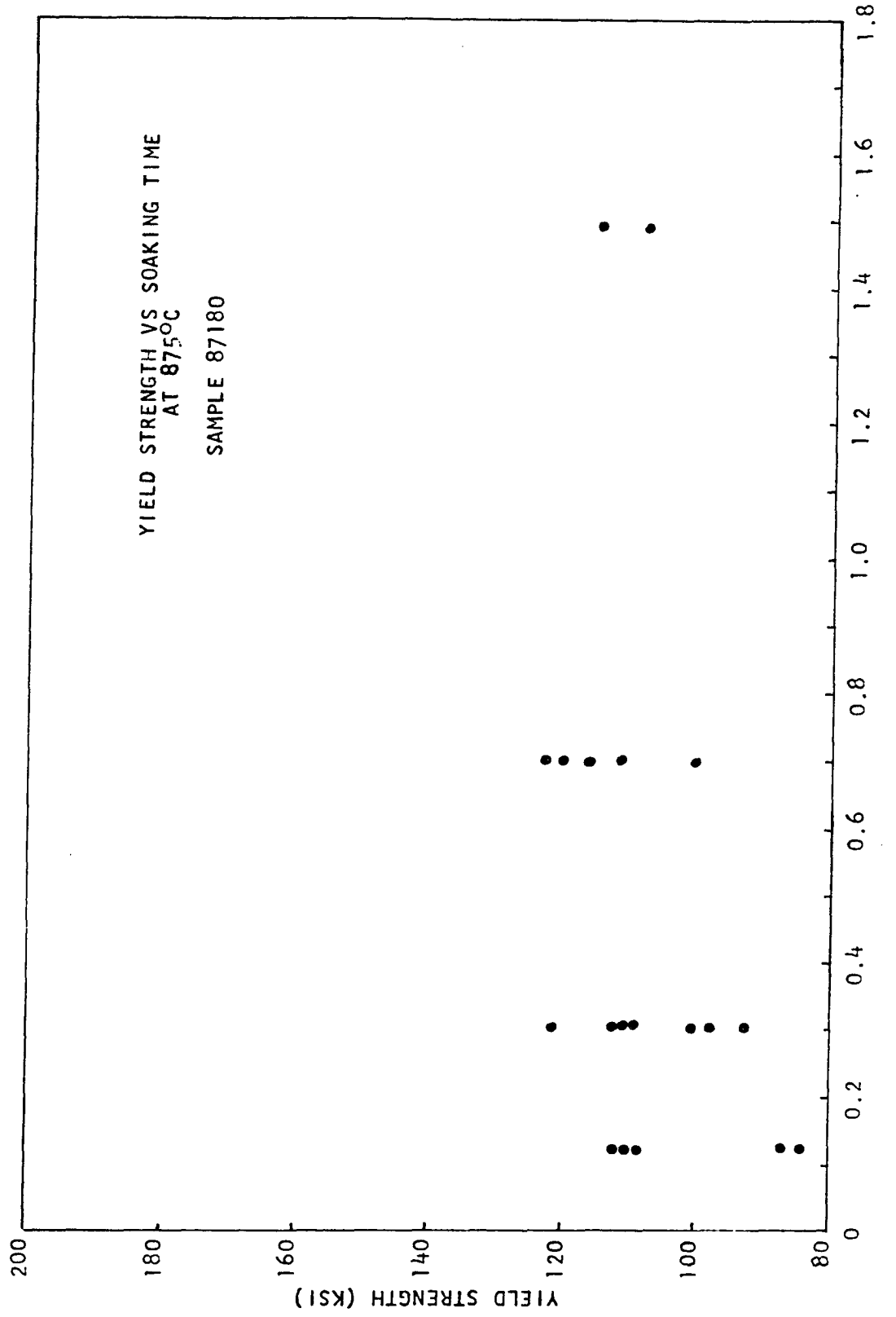


Figure 59

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

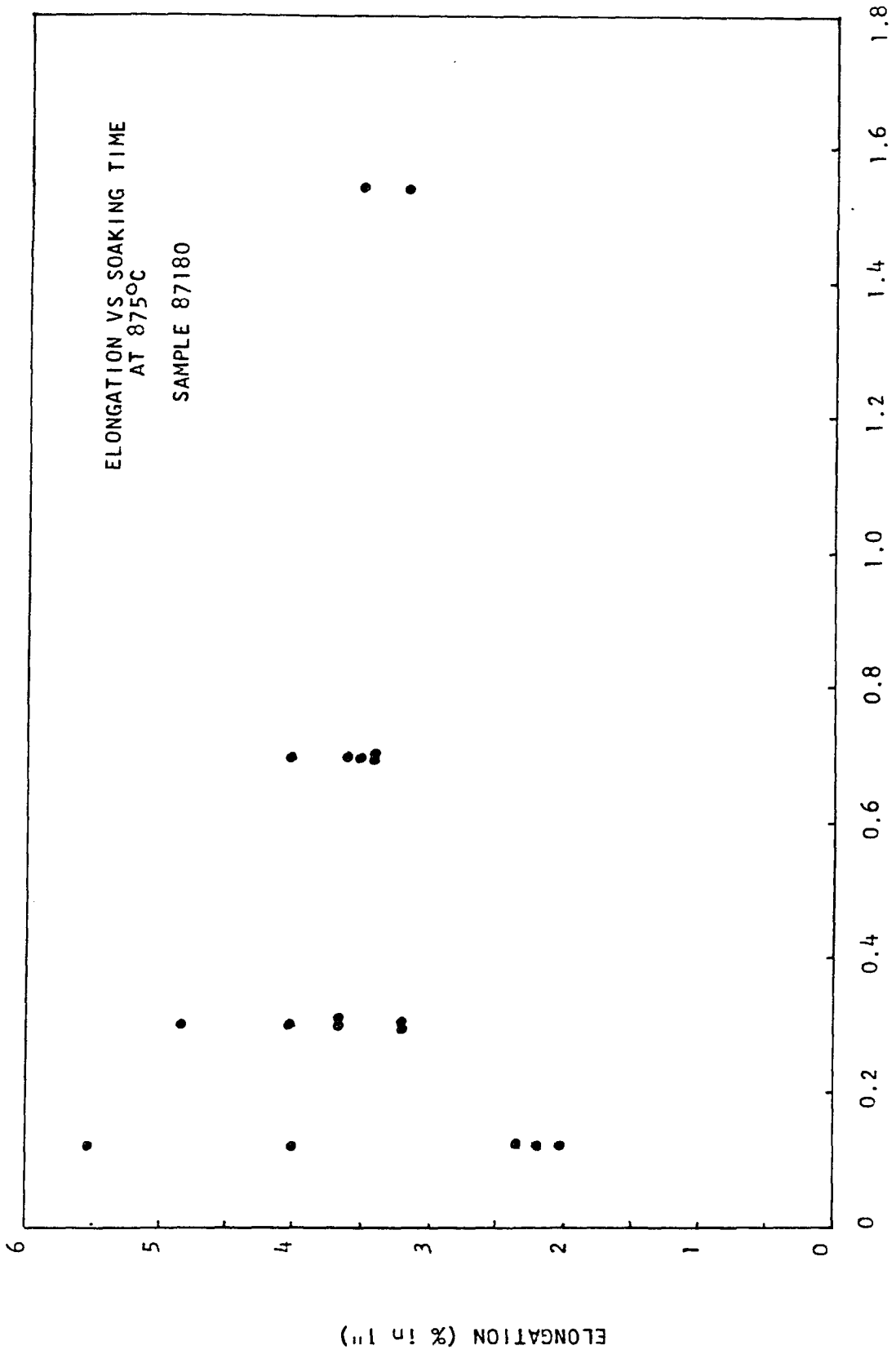


Figure 60

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

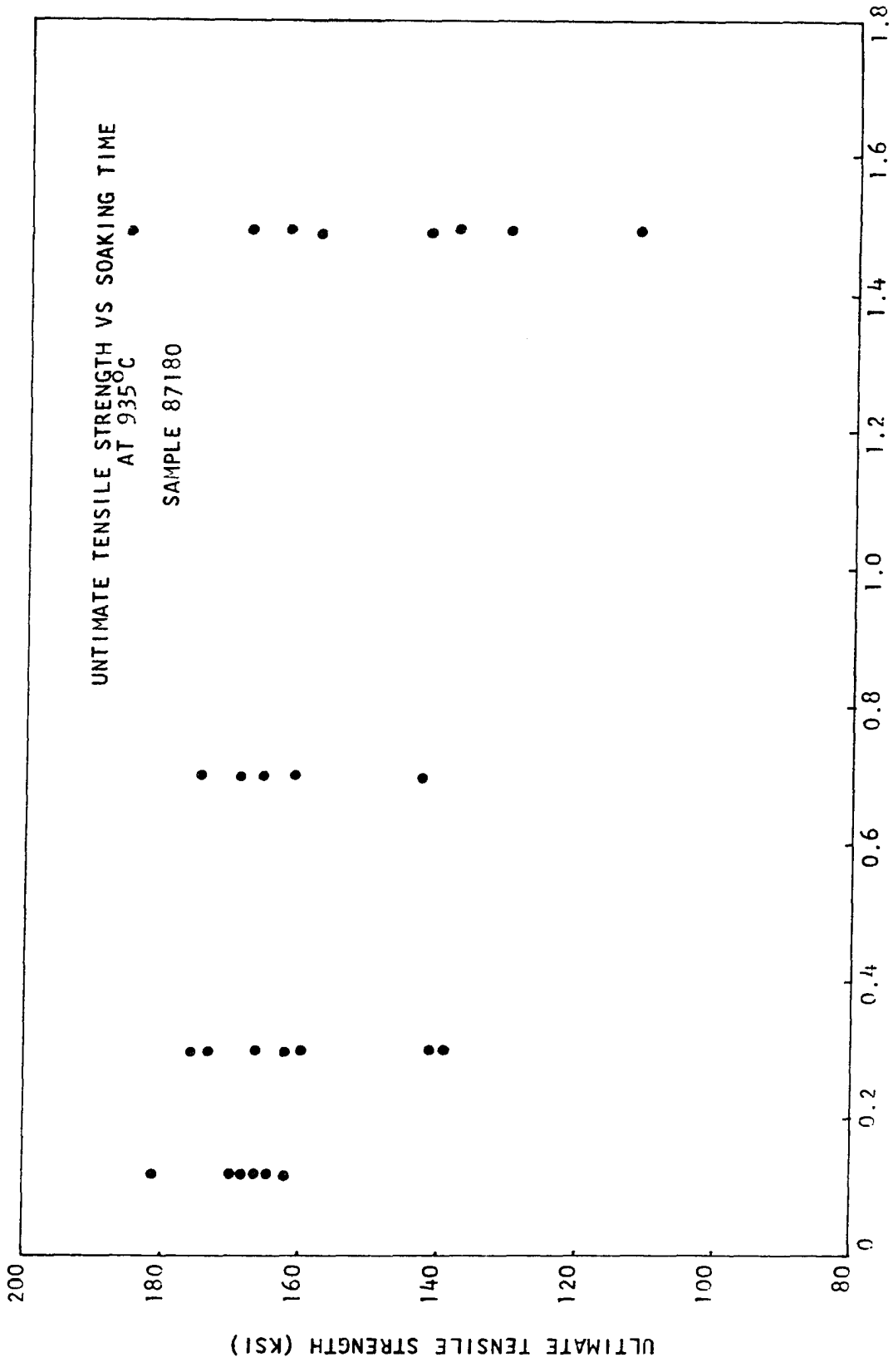


Figure 61

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

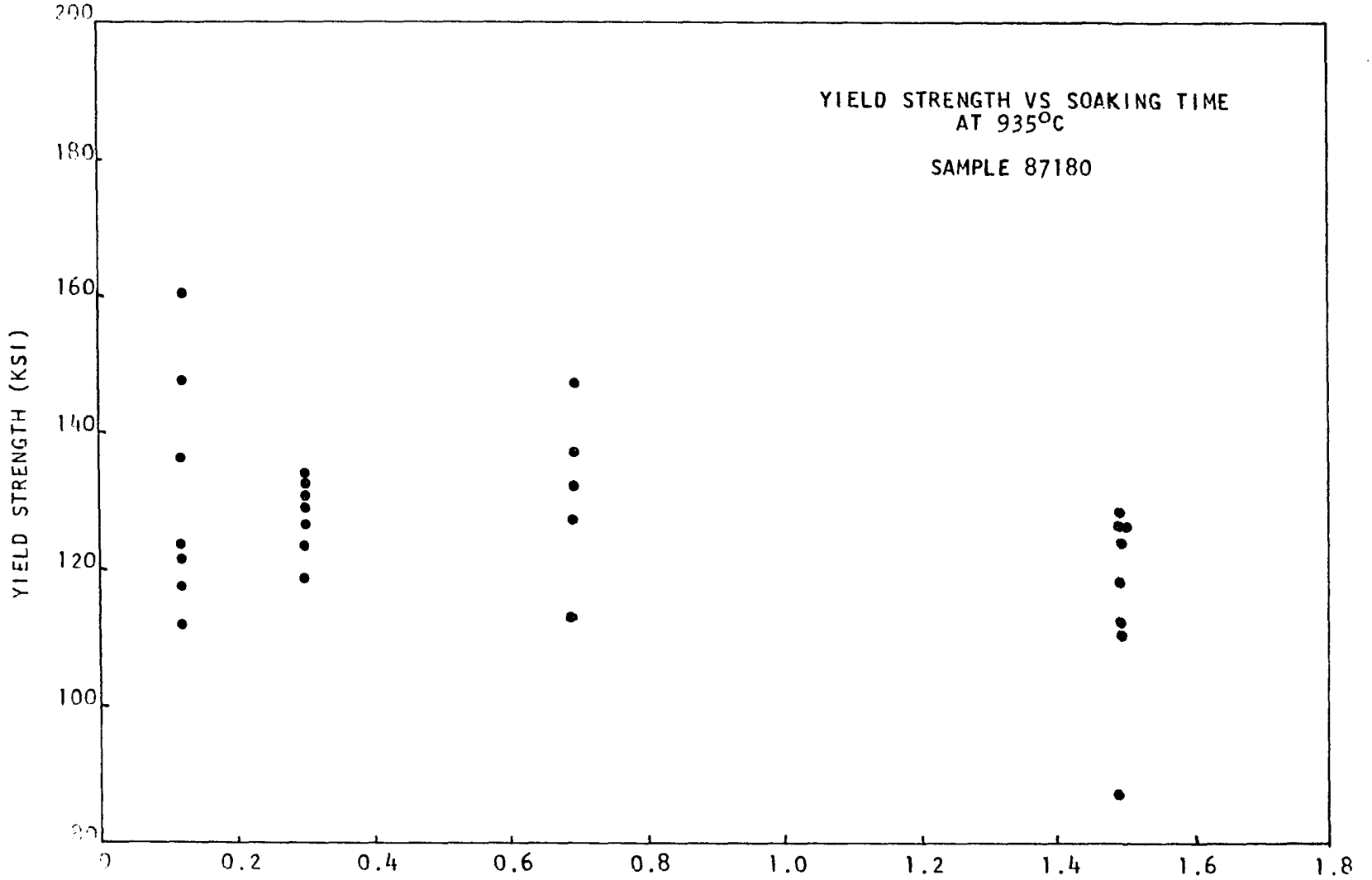


Figure 62

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

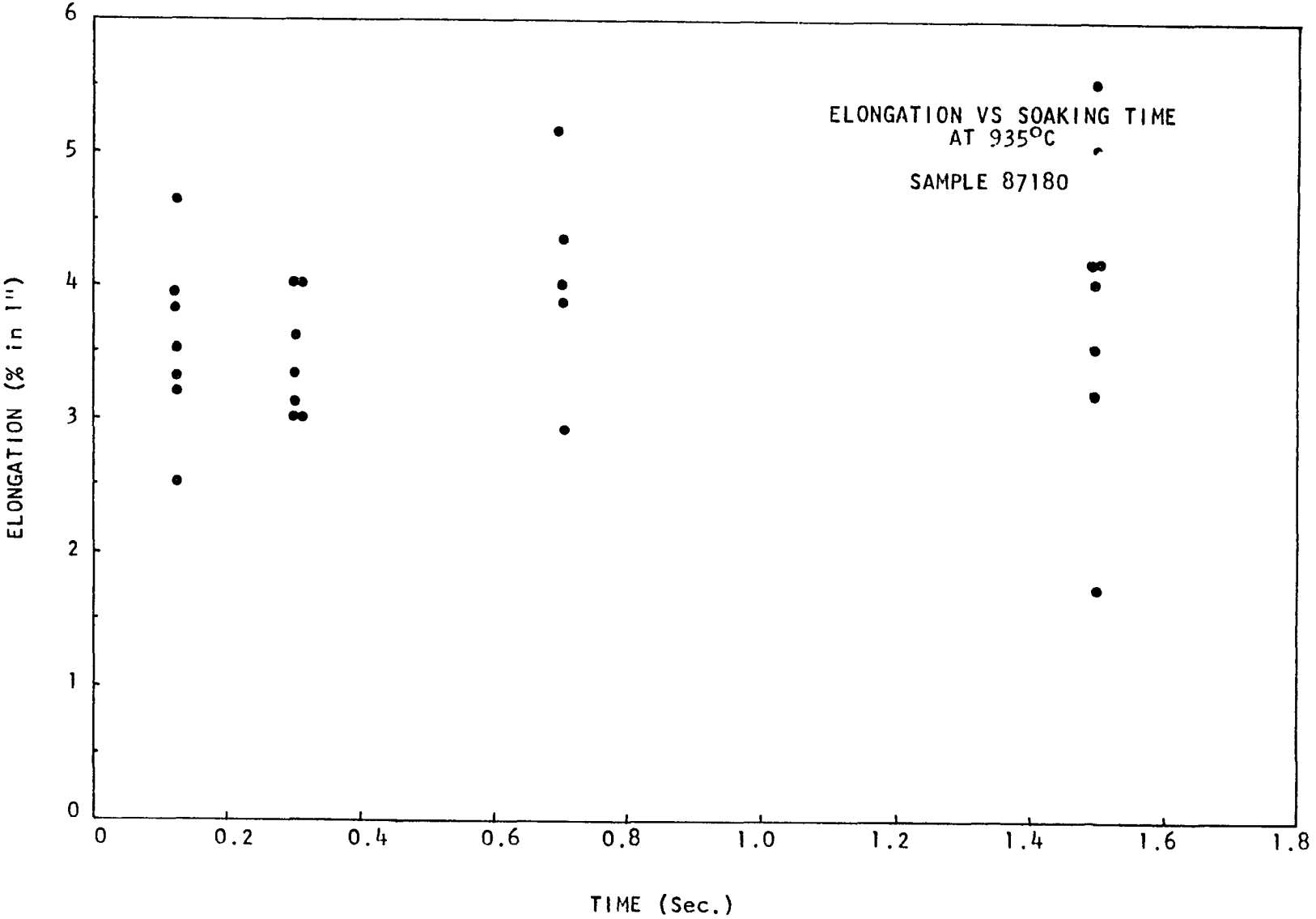


Figure 63

VITA AUCTORIS

BORN: May 20, 1941, Edmonton, Alberta,
Son of James D. Wallbridge and
the late Gwendolyn R. Wallbridge

SCHOOLING: Edmonton Public Schools

UNIVERSITY: University of Alberta, Edmonton, Alberta

1964-65 Research Assistant,
Universities Alberta and Windsor

PUBLICATION: "TRANSFORMATIONS IN Fe-Cr ALLOYS",
J.M. Wallbridge and J. Gordon Parr.
J I S I, 204, 1966, 11

PROFESSIONAL SOCIETIES:
Iron and Steel Institute
Institute of Metals
American Society for Metals
National Association of Corrosion Engineers

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.